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This manual presents two options which allow determination of stationary source $PM_{2.5}$ to be measured in conjunction with PM_{10} and it can be measured as $PM_{2.5}$ only. When determining both $PM_{2.5}$ and PM_{10}, either the Constant Sampling Rate (CSR) procedures or the Exhaust Gas Recycle (EGR) sampling system can be used. When $PM_{2.5}$ is the only size fraction of interest the CSR procedures are selected. This application guide should be used as a companion to the application guides for CSR and EGR. Stack gas is sampled at multiple points using an in-stack inertial sampler with a constant flow rate. For $PM_{2.5}$ measurements only, the maximum allowable error due to anisokinetic sampling is ±10% for 2.5 μm particles. The range of duct velocities permitted for a nozzle with this maximum allowable error is broad enough that rarely is it necessary to break a traverse into subtraverses with different sampling nozzles.

The sampling device described in this manual is Cyclone IV of the SRI/EPA five-stack series cyclone. This device provides a 2.5 μm size cut at a flow rate of approximately 0.36 dscfm; the precise flow rate depends on local stack conditions. These procedures specify the precise flow rate for $PM_{2.5}$ separately and PM_{10} when the described cyclone particle sizers are used.

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FOREWORD

Measurement and monitoring research efforts are designed to anticipate environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations, and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, North Carolina, has responsibility for: assessment of environmental monitoring technology and systems for air, implementation of agency-wide quality assurance programs for air pollution measurement systems, and supplying technical support to other groups in the Agency including the Office of Air and Radiation, the Office of Toxic Substances, and the Office of Solid Waste.

The environmental effects of $PM_{2.5}$ particulate matter may be of concern to the Agency. Acceptable measurement methodology is critical for proper assessment of the impact on the environment of these emissions from stationary sources. Preparation of a manual which specifies measurement procedures is a key component for assuring reliable test data. This manual was prepared to describe maintenance and operating procedures for measurement of $PM_{2.5}$ emissions from stationary sources.

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ABSTRACT

This manual presents two options which allow determination of stationary source $PM_{2.5}$ emissions. $PM_{2.5}$ can be measured in conjunction with PM_{10} and it can be measured as $PM_{2.5}$ only. When determination of both $PM_{2.5}$ and PM_{10} is the object of a test series, either the Constant Sampling Rate (CSR) procedures or the Exhaust Gas Recycle (EGR) sampling system can be used. When $PM_{2.5}$ is the only size fraction of interest the CSR procedures are selected. This application guide should be used as a companion to the application guides for CSR and EGR. With all of the options, stack gas is sampled at multiple points using an in-stack inertial sampler with a constant flow rate. The operating principle of the CSR procedures limit errors due to anisokinetic sampling to within specified limits related to the maximum particle size of interest. For $PM_{2.5}$ measurements only, the maximum allowable error due to anisokinetic sampling is ±10% for 2.5 μm particles. The range of duct velocities permitted for a nozzle with this maximum allowable error is broad enough that rarely is it necessary to break a traverse into subtraverses with different sampling nozzles.

The sampling device described in this manual is Cyclone IV of the SRI/EPA five-stage series cyclone. This device provides a 2.5 μm size cut at a flow rate of approximately 0.36 dscfm; the precise flow rate depends on local stack conditions. These procedures specify the precise flow rate for $PM_{2.5}$ measurements when Cyclone IV is used alone and for both PM_{10} and $PM_{2.5}$ measurements when Cyclone IV is used in conjunction with Cyclone I as a two stage inertial sampler.

CONTENTS

Foreword iii
Abstract iv
Figures viii
Tables x

1. Introduction 1
2. $PM_{2.5}$ Operating Principles and Hardware Requirements 3
   - Operating Principles 3
     - Error due to anisokinetic sampling 3
       - $PM_{2.5}$ emission rate 4
       - $PM_{2.5}$ fraction 6
     - Errors due to spatial variation 6
   - Sampling Hardware 6
   - Cyclones 7
     - Performance determination 7
     - Determination of collection efficiency of cyclone and upstream hardware 8
     - Performance specifications 10
     - SRI/EPA Cyclone IV 10
   - Cascade Impactors 10
     - Performance determination 10
     - Performance specifications 10
   - Sampling Nozzles 15
3. Calibration 19
4. Presampling Activities 20
5A. Sampling Parameters: $PM_{2.5}$ Only 21
   - Preliminary Setup Parameters 21
     - Traverse points 21
     - Stack temperature, velocity, and gas constituents 21
   - Setup Calculations for a Single-Stage Cyclone Sampler 23
     - Sample flow rate 23
     - Nozzle selection 25
   - Setup Calculations for Cascade Impactor Samplers 26
     - Sample flow rate 26
     - Nozzle selection 27
   - Sample Orifice Pressure Drop 27
   - Dwell Time 27
   - Performing the Calculations 28
   - Symbols for Section 5A 34

CONTENTS (Continued)

Page

5B. Sampling Parameters: $PM_{2.5}$ in Conjunction with PM_{10} 36
Preliminary Setup Parameters 39
Traverse points 39
Stack gas temperature, velocity, and gas constituents 42
CSR Setup Calculations 42
Sample flow rate selection for a two-stage cyclone sampler 42
Nozzle selection for a two-stage cyclone sampler 44
Sample flow rate selection for cyclone impactor samplers 46
Nozzle selection for cascade impactor samplers 47
Sample orifice pressure drop 47
Dwell time 47
Worksheets for CSR setup calculations 48
EGR Setup Calculations 48
Sample flow rate selection for a two-stage cyclone sampler 48
Nozzle selection for a two-stage cyclone sampler 56
Target pressure differentials (ΔH, ΔP_t, ΔP_r) 56
Symbols for Section 5B 63
6. Taking the Sample 66
7. Sample Retrieval 67
Recovery of the Particulate Mass 67
Moisture Determination 68
8. Postsampling Checks 69
9A. Data Analysis for $PM_{2.5}$ Sampling 70
Velocity-Weighted Averages 70
Dry Gas Meter Volume 70
Water Vapor Volume 70
Percent Moisture Content 71
Stack Gas Molecular Weight 71
Stack Gas Viscosity 71
Sample Flow Rate 71
Sampler Inlet Reynolds Number 72
Sampler D_{50} 72
Stack Gas Velocity 73
Nozzle Velocity 73
Nozzle ΔP Limits 73
Percent Isokinetic Sampling 73
Concentration 74
Acceptance Criteria 74
Symbols for Section 9A 75

CONTENTS (Continued)

Page

9B. Data Analysis for $PM_{2.5}$ and PM_{10} Sampling 77
Data Analysis for CSR 77
Velocity-weighted averages 77
Dry gas meter volume 77
Water vapor volume 78
Percent moisture content 78
Stack gas molecular weight 78
Stack gas viscosity 78
Sample flow rate 79
Sampler inlet Reynolds number 79
Sampler D_{50} 79
Stack gas velocity 80
Nozzle velocity 80
Nozzle ΔP limits 80
Percent isokinetic sampling 81
Concentration 81
Data Analysis for DGR 81
Dry gas meter volume 81
Water vapor volume 81
Percent moisture content 81
Water fraction in mixed gas 82
Stack gas molecular weight 82
Mixed gas viscosity 82
Sample flow rate 83
Total (cyclone) flow rate 83
Percent recycle 83
Sampler inlet Reynolds number 84
Sampler D_{50} 84
Stack gas velocity 85
Percent isokinetic sampling 85
Concentration 85
Acceptance Criteria 85
Symbols for Section 9B 87
10. Maintenance 90
11. Auditing Procedures 91
12. Recommended Standards for Establishing Traceability 92

References 93

FIGURES

Number		Page
2-1	Velocity ratio R, duct velocity/nozzle velocity, versus duct velocity giving aspiration coefficient of 1.1 (upper curves) and 0.9 (lower curves) for particles with aerodynamic diameter of 2.5 μm and gas viscosities ranging from 160 to 280 micropoise	5
2-2	Efficiency envelope for $PM_{2.5}$ cyclone samplers	12
2-3	Cyclone IV dimensions	13
2-4	Efficiency envelope for $PM_{2.5}$ cascade impactor samplers	14
2-5	$PM_{2.5}$ nozzle design	17
5A-1	Minimum number of traverse points for CSR	22
5A-2	CSR Worksheet IA - Sample flow rate and orifice ΔH calculations for $PM_{2.5}$	29
5A-3	CSR Worksheet IIA - Nozzle selection for $PM_{2.5}$	31
5A-4	CSR Worksheet IIIA - Dwell time calculations	33
5B-1	Flow rate range for acceptable PM_{10} and $PM_{2.5}$ sampling	38
5B-2	Measurement tolerance as a function of stack conditions	40
5B-3	Minimum number of traverse points for CSR	41
5B-4	CSR Worksheet IB - Sample flow rate and orifice ΔH calculations for PM_{10} and $PM_{2.5}$	49
5B-5	CSR Worksheet II - Nozzle selection for PM_{10} and $PM_{2.5}$	51
5B-6	CSR Worksheet IIIB - Dwell time calculations	53
5B-7	EGR Worksheet IB - Total (Cyclone) flow rate for PM_{10} and $PM_{2.5}$	58

FIGURES (Continued)

Number		Page
5B-8	EGR Worksheet IIB - Orifice ΔH for PM_{10} and $PM_{2.5}$	60
5B-9	EGR Worksheet IIIB - Total flow LFE ΔP_t and recycle LFE ΔP_r for PM_{10} and $PM_{2.5}$	61

TABLES

Number		Page
2-1	Particle sizes and nominal gas velocities for efficiency performance tests of cyclones	9
2-2	Performance specifications for source $PM_{2.5}$ cyclone samplers	11
2-3	$PM_{2.5}$ nozzle diameters and velocity limits	16
2-4	$PM_{2.5}$ nozzle geometries	18
5-1B	Projected variation of Cyclone IV D_{50} to achieve a 10 μm D_{50} in Cyclone I	37
5-2B	Projected variation of Cyclone I D_{50} for a 2.5 μm D_{50} in Cyclone IV	37

SECTION 1

INTRODUCTION

Airborne particulate matter of less than 2.5 μm aerodynamic diameter is of interest because these particles are respirable. Measurement of source particulate emissions in this size band ($PM_{2.5}$) is subject to much the same considerations as particulate matter of less than 10 μm aerodynamic diameter PM_{10}) and, therefore, will require similar sampling procedures.

Two methods have been developed for determination of PM_{10} emissions. One method uses the principle of Exhaust Gas Recycle (EGR) to meet the constraints of particle sizing (constant flow rate through the sampling device) and representative sampling (isokinetic sampling at the number of traverse points prescribed by Method 1). The second method, Constant Sampling Rate, (CSR), limits error due to anisokinetic sampling and spatial variation to the level of more intrinsic errors, such as source fluctuations. A complete traverse of the sampling plane is synthesized from one or more runs operated within these limits. Although greater accuracy in mass concentration is achieved by the more stringent limits on isokinetic sampling exercised by the EGR method, development of new sampling hardware is required. The CSR method, on the other hand, uses existing Method 5 or Method 17 hardware.

Two options for $PM_{2.5}$ sampling are considered here: (1) measurement of $PM_{2.5}$ in junction with PM_{10} and (2) measurement of $PM_{2.5}$ only. When determination of both $PM_{2.5}$ and PM_{10} is the object of a test series, either CSR or EGR can be used. The procedures required for each method will be described in this text. When $PM_{2.5}$ is the only size fraction of interest, the effects of anisokinetic sampling are much less significant; consequently, the greater accuracy achieved by the EGR method becomes insignificant. For this reason, only CSR procedures will be described for this option.

This manual should be used as a companion to the operator's manuals for CSR and EGR for PM_{10} measurement (Farthing and Dawes, 1989, and Martin et al., 1989). Text here is confined to those changes in procedure or hardware required to measure $PM_{2.5}$. To simplify incorporating information presented here with EGR or CSR operating procedures for PM_{10}, this manual is organized in a manner identical to the PM_{10} operating manuals, with one significant difference. Because two options are available to the operator when sampling for $PM_{2.5}$, certain sections of this text will be repeated to present the procedures for each option separately and completely. For example, Section 5A presents setup calculations for measurement of $PM_{2.5}$ only, and Section 5B presents these same calculations for measurement of $PM_{2.5}$ along with PM_{10}.

Like the CSR and EGR operator's manuals, Section 2 of this text describes the hardware requirements and operating principles of a $PM_{2.5}$ sampling system. Calibration procedures and presampling activities are cited Sections 3 and 4. Section 5A presents the equations required to calculate the sampling parameters for $PM_{2.5}$ determination. Section 5B presents this same material for determination of $PM_{2.5}$ with PM_{10}. The steps to follow during a sample run are outlined in Section 6. Section 7 presents sample recovery procedures, and Section 8 references postsampling activities. Section 9A describes data analysis for $PM_{2.5}$ measurements, and Section 9B provides the same information for measurements of $PM_{2.5}$ with PM_{10}. Sections 10 and 11 cite recommended maintenance and auditing procedures, and Section 12 cites the recommended standards for establishing traceability.

SECTION 2

$PM_{2.5}$ OPERATING PRINCIPLES AND HARDWARE REQUIREMENTS

The emphasis of this section is two specific but related topics: 1) $PM_{2.5}$ operating principles and 2) $PM_{2.5}$ sampling hardware specifications. The relationship between the two topics is a shared objective. The main goal of the discussion associated with each topic is management of sampling error such that data of known and acceptable quality may be obtained. In general, sampling for $PM_{2.5}$ requires much the same considerations as PM_{10}. However, the smaller particle size associated with $PM_{2.5}$ has dictated some changes in operating principles and sampling hardware which will be discussed here.

OPERATING PRINCIPLES

The most significant difference between the PM_{10} sampling techniques previously developed and the $PM_{2.5}$ methodology described in this manual is the two options (measurement of $PM_{2.5}$ only or measurement of $PM_{2.5}$ in conjunction with PM_{10}) available to the operator when sampling for $PM_{2.5}$. The operating principles must encompass both of these options.

As stated previously in Section 1, when $PM_{2.5}$ is the only size fraction of interest, CSR procedures will be selected. When determination of both $PM_{2.5}$ and PM_{10} is the objective of a test series, either CSR or EGR may be selected as the operating method.

Error Due to Anisokinetic Sampling

For any given particle diameter, the anisokinetic sampling error may be expressed as the aspiration coefficient, which is defined as the ratio of measured concentration to actual concentration. Belyaev and Levin (1974) developed a semi-empirical relationship for aspiration coefficient, A, in terms of the particle Stokes number, K, and the ratio of stream velocity to nozzle velocity, R, where B is equal to $(2 + 0.617/R)K$:

$$A = 1 + (R-1)\frac{B}{B+1} \qquad (2\text{-}1)$$

where
- R = ratio of stream velocity to nozzle velocity, v/u
- K = particle Stokes number with respect to the nozzle, $\tau v/d$
- d = nozzle diameter
- τ = particle relaxation time ($CD^2/18\mu$)
- C = Cunningham slip factor
- D = particle aerodynamic diameter
- μ = gas viscosity

From the above equation, it is seen that, for given stack conditions and particle size, limiting the anisokinetic sampling error becomes a question of limiting the velocity ratio, R. In other words, for a given limit on error due to an isokinetic sampling, there will be maximum and minimum values of R (R_{max} and R_{min}) which yield results within the stated limits. It may also be noted from the equation that B is proportional to particle diameter squared. This indicates that anisokinetic sampling error decreases with decreasing particle size. In other words, when sampling for $PM_{2.5}$ emissions, the velocity ratio, R, could be outside the 0.9 to 1.1 range stated for total emissions in Methods 5 and 17 and still retain equivalent accuracy.

$PM_{2.5}$ Emission Rate ----

When the EGR method is used to determine the $PM_{2.5}$ emission rate in conjunction with PM_{10}, the nozzle velocity at each traverse point must be adjusted to remain within ±10% of the isokinetic velocity as in Method 5. This limits the velocity ratio, R, to 1.0 ±0.1, which corresponds to anisokinetic sampling errors of less than ±10% for both PM_{10} and $PM_{2.5}$.

When using the CSR method to determine $PM_{2.5}$ emission rate in conjunction with PM_{10}, the limits on velocity ratio given for PM_{10} in the CSR operators manual should be used. This limits anisokinetic sampling error for 10 μm particles to ±20%. Because of the smaller particle size, the corresponding anisokinetic sampling error for 2.5 μm particles is much less than ±20%.

When the CSR method is used to determine $PM_{2.5}$ emission rate only, limits on the error due to anisokinetic sampling are reduced from the PM_{10} limits on the error level of ±20% to ±10%. Solving equation 2-1 for R as a function of stream velocity, v, gas viscosity, μ, sample flow rate, Q, and particles with aerodynamic diameter of 2.5 μm, the series of curves shown in Figure 2-1 are defined. The upper curves give R_{max} and correspond to the upper limit (1.1) on the aspiration coefficient, A. The lower curves give R_{min} and correspond to the lower limit on A (0.9). As can be seen from the figure, the limits on R are quite broad at the lower stream velocities, but approach limits of ±10% at high stream velocities.

A comparison of the graph in Figure 2-1 with a similar graph generated for PM_{10} shows that, for a given stream velocity, the range of acceptable coefficient values for $PM_{2.5}$ is greater than that for PM_{10}, even though more restrictive limits on the aspiration coefficient are required for $PM_{2.5}$ ($0.9 \leq A \leq 1.1$ for $PM_{2.5}$; $0.8 \leq A \leq 1.2$ for PM_{10}). In other words, the smaller particle size of $PM_{2.5}$ makes it possible to set a more stringent limit on error due to anisokinetic sampling without producing a similar restriction on the range of velocity ratios.

Actual $PM_{2.5}$ sampling error at most sources when the CSR method is used will be less than ±10% for two reasons. First, point-by-point R values will usually be something less than the limits, R_{min} and R_{max}, and cancellation of errors will occur because R-1 values will be negative at some points and positive at others. Second, the curves shown in Figure 2-1 were determined assuming a monodisperse sample of 2.5 μm particles. In actuality, the $PM_{2.5}$ sample is composed of particles with aerodynamic diameters that are less than 2.5 μm.

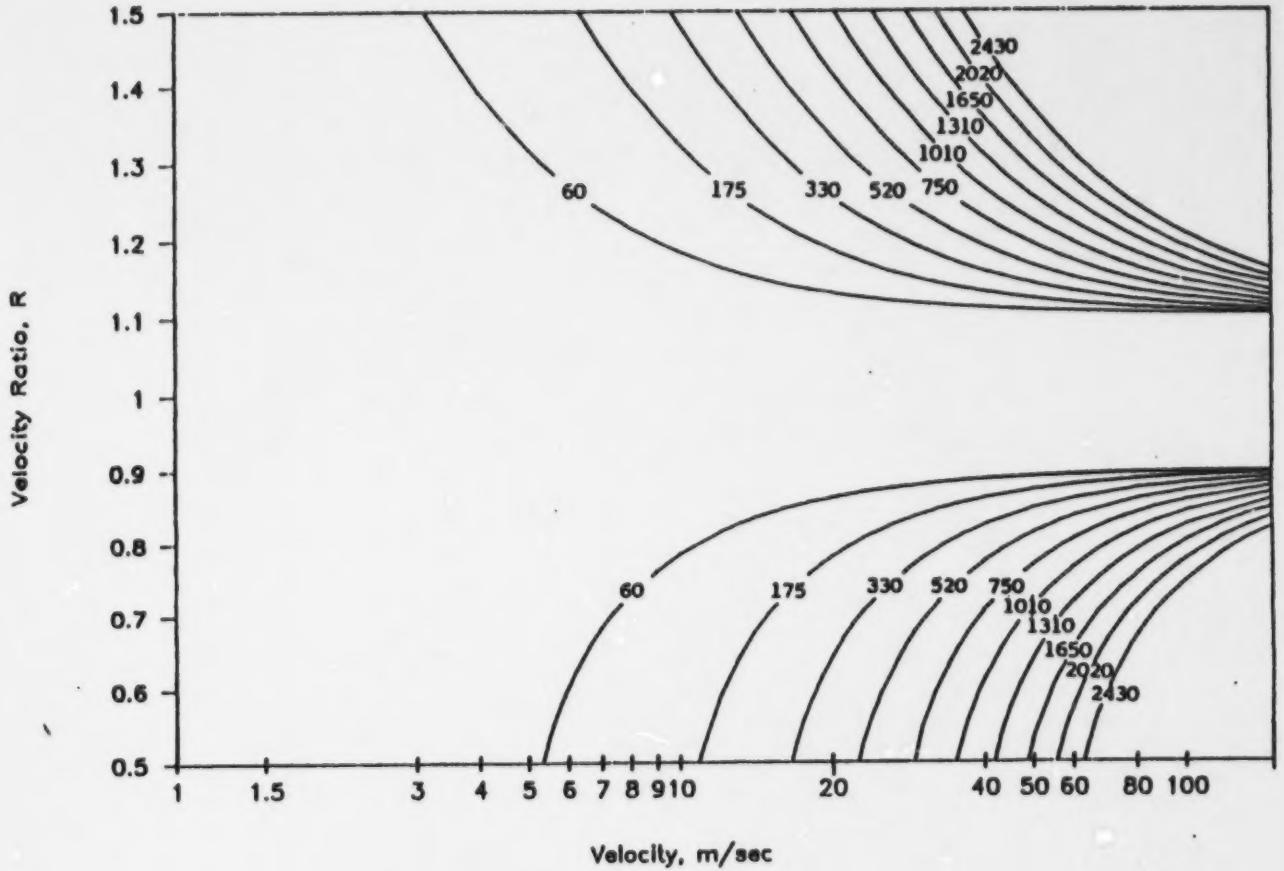


Figure 2-1. Velocity ratio R, duct velocity/nozzle velocity, versus duct velocity giving aspiration coefficient of 1.1 (upper curves) and 0.9 (lower curves) for particles with aerodynamic diameter of 2.5 um and gas viscosities ranging from 160 to 280 micropoise.

$PM_{2.5}$ Fraction ----

For a given source, the limit on percentage error in measurement of the $PM_{2.5}$ fraction is approximately the quantity

$$100(R-1)(1-f_{2.5})$$

where

R = the minimum or maximum value of velocity ratio experienced during the sampling run

$f_{2.5}$ = the $PM_{2.5}$ fraction

When the CSR method is used, limits on acceptable values of R are determined by setting the error to ±10%. The limits then become

$$R_{min} = 1 - \frac{0.1}{1 - f_{2.5}} \qquad (2\text{-}2)$$

and

$$R_{max} = 1 + \frac{0.1}{1 - f_{2.5}} \qquad (2\text{-}3)$$

As can be seen from these equations, determination of these limits requires an estimate of the $PM_{2.5}$ fraction. Therefore, it may be necessary to repeat a run which used a poor estimate of $f_{2.5}$ and experienced substantial velocity variation across the sampling plane.

When the $PM_{2.5}$ fraction is determined with the EGR method, the limits on R are set at 1.0 ±0.1 as discussed previously. For typical particle size distributions, this will result in sampling errors of much less than ±10%.

Errors Due to Spatial Variation

The lower inertia of $PM_{2.5}$ would lead one to expect less stratification of particle concentration across a duct than with PM_{10}. Unfortunately, there is not sufficient data available to evaluate this effect. Therefore, the number of traverse points specified by the chosen sampling method (EGR or CSR) for measurement of PM_{10} will be required for $PM_{2.5}$, whether measured in conjunction with PM_{10} or not.

SAMPLING HARDWARE

The sampling system used to measure $PM_{2.5}$ for either the CSR or EGR method is the same as for PM_{10} with the exception of the particle sizing device. When $PM_{2.5}$ is the only size fraction of interest, a single-stage cyclone or a cascade impactor may be used as the sampling device. When determination of both $PM_{2.5}$ and PM_{10} is the objective of a test series and CSR is the chosen operating method, either a two-stage cyclone or a cascade impactor may be used as the sampling device. The only device that has been

developed for the EGR method at present is a two-stage cyclone (one stage to cut at 10 μm and one stage to cut at 2.5 μm).

Before any particle sizing device is used as a $PM_{2.5}$ sampler, it must be shown to meet some specific performance requirements. The procedures by which this may be done are discussed in the following sections for both single-stage and multi-stage devices (cyclones and cascade impactors, respectively). The specific performance requirements for each of these devices are also given.

CYCLONES

The objectives of performance determination procedures for $PM_{2.5}$ cyclone samplers are twofold: (1) to calibrate the cyclone (i.e., establish the relationship between collection efficiency, flow rate, gas viscosity, and gas density for the given device) and (2) to determine that cyclone performance satisfies the performance specifications with the upstream hardware in place. This upstream hardware may consist of a samplinq nozzle (when measuring $PM_{2.5}$ only) or another cyclone (when measuring $PM_{2.5}$ in conjunction with PM_{10}).

Performance Determination

In order to determine that a given cyclone meets the requirements for use as a $PM_{2.5}$ device, the performance determination procedures outlined in the following text must be performed.

1. Particle Generation. The particle generating system should be the same as that described in Section 2 of the CSR operator's manual.

2. Wind Tunnel. The wind tunnel used for performance determination of $PM_{2.5}$ samplers should be the same as that required for PM_{10} as outlined in the CSR operator's manual.

3. Cyclone Calibration. The procedures outlined for calibration of the PM_{10} cyclone in Section 2 of the CSR operator's manual should be followed when calibrating the $PM_{2.5}$ cyclone. The range of particle sizes used for calibration should be 1.0 to 4.0 μm.

4. $PM_{2.5}$ Flow Rate. To determine the empirical relationship between $PM_{2.5}$ flow rate and gas conditions, the cyclone calibration procedures must be performed for at least three temperatures. The D_{50}'s must be between 1.25 and 3.75 μm and measured at temperatures within 60°C of the temperature at which the cyclone will be used. In addition, one of the measured D_{50}'s must be 2.5 ±0.25 μm.

Linear regression analysis is used to determine the relationship between the dimensionless parameters, Ψ_{50} (= 0.5 Stk_{50}) and Re. The equations for Ψ_{50} and Re, where Stk_{50} is the Stokes number giving 50% collection and Re is the Reynolds number of the gas entering the cyclone are presented here:

$$\Psi_{50} = 0.5Stk_{50} = D_{50}^2\left(\frac{4CQ}{18\pi\mu d^3}\right) \quad (2\text{-}4)$$

and

$$Re = \frac{4\rho Q}{\pi\mu d} \quad (2\text{-}5)$$

where Q = gas flow rate through the cyclone at the inlet conditions
μ = gas viscosity
d = diameter of the cyclone inlet
ρ = gas density at the cyclone inlet
C = Cunningham slip correction factor

With the substitution of a D_{50} of 2.5 μm into the resulting relationship, the flow rate for $PM_{2.5}$ measurements is predicted as a function of gas conditions.

Determination of Collection Efficiency of Cyclone and Upstream Hardware

Because the cyclone is used in actual sampling situations with some type of upstream hardware in place, it is necessary to establish that this hardware does not disturb the particle sizing characteristics of the cyclone as determined by the calibration procedures. As mentioned previously, this upstream hardware can take two forms: a sampling nozzle if the cyclone is used for determination of $PM_{2.5}$ only, or a PM_{10} cyclone and the appropriate connective tubing if the cyclone is used for determination of $PM_{2.5}$ with PM_{10}.

If the cyclone is to be used in the first configuration (with a sampling nozzle), the procedures outlined for the determination of cyclone/nozzle collection efficiency in the CSR operator's manual should be followed. The sample flow rate used should be that which provides a cyclone D_{50} of 2.5 μm. The particle sizes and stream velocities that should be tested are shown in Table 2-1.

If the cyclone is to be used in the latter configuration (downstream of the PM_{10} cyclone and appropriate connective tubing), it is necessary to demonstrate that the geometry of the upstream hardware does not affect the behavior of the $PM_{2.5}$ device. To do this, one collection efficiency test should be performed with the sampling unit for each of the particle diameters shown in Table 2-1. The sampling flow rate should be set to provide a D_{50} in the $PM_{2.5}$ cyclone between 2 and 3 μm.

At the completion of the sampling runs, the overall and sampler-only collection efficiencies (E_{tot} and E_{sam}) should be determined as outlined in the CSR operator's manual. For each run, a plot of E_{tot} and E_{sam} as functions of particle size (D_p) should be prepared on semilog paper, with smooth curves drawn through all sizes used. With this plot, D_{50} for E_{sam} can be defined as the diameter at which the E_{sam} curve crosses 50% efficiency.

TABLE 2-1. PARTICLE SIZES AND NOMINAL GAS VELOCITIES FOR EFFICIENCY PERFORMANCE TESTS OF CYCLONES

Particle Size (μm)[a]	Target Gas Velocity (m/s)		
	7 ±1.0	15 ±1.5	25 ±2.5
1.25 ±0.25	X	X	X
2.0 ±0.25	X	X	X
2.5 ±0.25	X	X	X
5.0 ±0.50	X	X	X
10.0 ±0.50	X	X	X

Note: The total number of test points is 30 (minimum of two replicates for each combination of gas velocity and particle size).

[a]Mass median aerodynamic diameter.

Performance Specifications

The performance specifications for $PM_{2.5}$ cyclone samplers are shown in Table 2-2. To be acceptable for use, the D_{50} for the sampler (determined from the E_{sam} curve as described previously) must be 2.5 ±0.25 μm. In addition, all data points used to determine the E_{tot} curves must meet the criteria given for collection efficiency. Criteria are given for cyclones used to determine $PM_{2.5}$ only and for those used to determine $PM_{2.5}$ in conjunction with PM_{10}. Devices that will be used in both configurations must be shown to meet both criteria. The efficiency envelope is illustrated in Figure 2-2.

SRI/EPA Cyclone IV

One sampling device known to meet $PM_{2.5}$ cyclone performance specifications is the commercially available version of Cyclone IV, the fourth stage of the SRI/EPA Five-Stage Series Cyclone. The critical inner dimensions of this cyclone are shown in Figure 2-3. Laboratory calibrations (Farthing and Williamson, 1985) have shown that Cyclone IV produces a 2.5 μm D_{50} at a flow rate of approximately 0.36 dscfm.

CASCADE IMPACTORS

While cascade impactors have been recognized as viable sampling devices for the measurement of $PM_{2.5}$ and PM_{10}, they are <u>not</u> recommended for widespread use because of the potential for error and interferences inherent in such devices. These problems would tend to increase the concentration at smaller particle diameters which can be critical to measurements of this type. To avoid these errors, an experienced operator is required.

Performance Determination

The performance determination procedures for cascade impactors as $PM_{2.5}$ devices will be the same as outlined for PM_{10} in the CSR operator's manual with one exception. Because of the smaller particle size associated with $PM_{2.5}$, the first $PM_{2.5}$ stage will be far enough removed from the sampling nozzle to be unaffected by it. For that reason, it will not be necessary to determine the relationship between Stk_{50} and nozzle inlet diameter for the first $PM_{2.5}$ stage.

Performance Specifications

The performance specifications for a candidate $PM_{2.5}$ impactor stage are shown in Figure 2-4. As can be seen from the figure, the acceptance envelope for cascade impactors is analogous to that for cyclones with the exception that the abscissa has been changed from aerodynamic particle diameter to values of square root of Ψ/Ψ_{50}. To determine if a given impactor stage meets the performance criteria, efficiency versus the square root of Ψ/Ψ_{50} should be plotted. All data must fall within the banded region of Figure 2-4 if the stage is to be accepted.

TABLE 2-2. PERFORMANCE SPECIFICATIONS FOR SOURCE $PM_{2.5}$ CYCLONE SAMPLERS

Parameter	Units	Specification
50% cut point (D_{50})	μm	2.5 ±0.25 μm aerodynamic diameter
Collection Efficiency	%	
$PM_{2.5}$ only		Collection efficiency should fall within envelope specified in text and Figure 2-2
$PM_{2.5}$ with PM_{10}		Collection efficiency should change by less than ±10% from calibration values

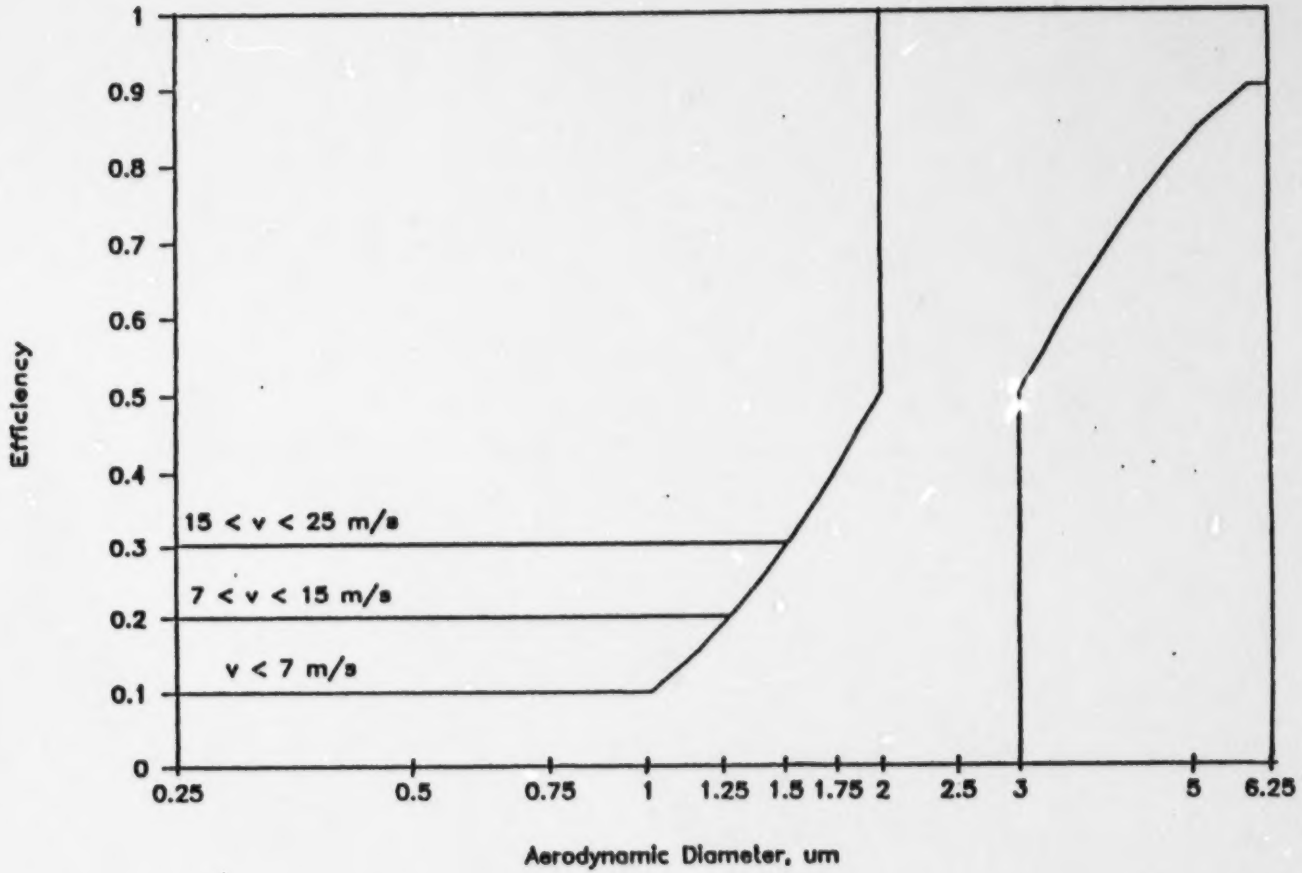
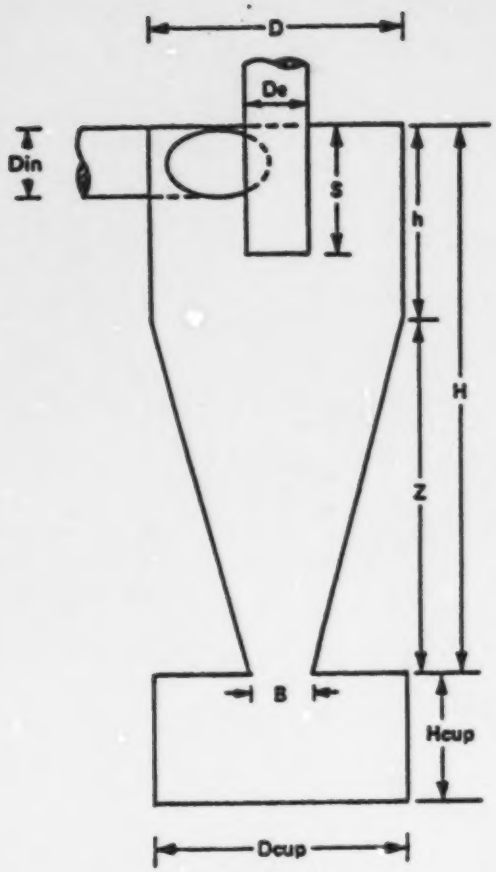


Figure 2-2. Efficiency envelope for $PM_{2.5}$ cyclone samplers.



DIMENSIONS(CM)

CYCLONE IV	Din .51	RELATIVE TO Din								
		D	De	B	H	h	Z	S	Hcup	Dcup
		4.98	1.16	2.14	5.15	2.02	3.57	1.14	4.35	5.14

Figure 2-3. Cyclone IV dimensions.

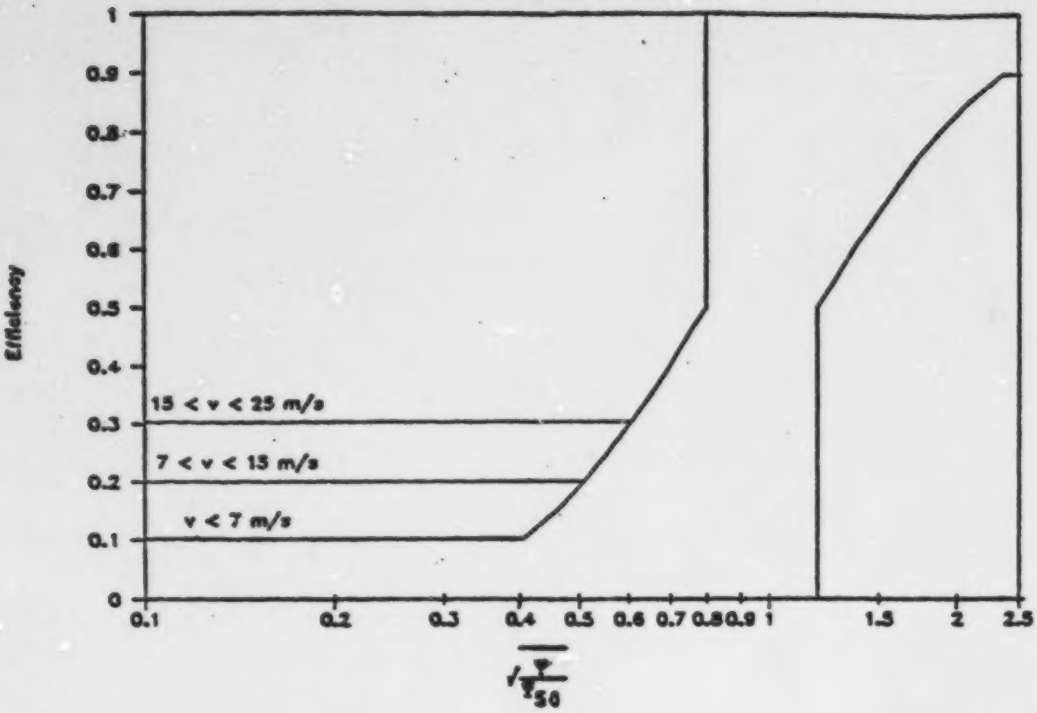


Figure 2-4. Efficiency envelope for $PM_{2.5}$ Cascade impactor samplers.

SAMPLING NOZZLES

Because the limits on velocity ratio, R, are greater for the measurement of $PM_{2.5}$ than PM_{10}, fewer nozzle sizes will be necessary without increasing the frequency of tests requiring more than one nozzle size to complete a traverse. The set of nozzle diameters found to provide a sufficient number of increments is shown in Table 2-3. The nozzle velocity corresponding to each diameter for the Cyclone IV $PM_{2.5}$ flow rate at the given stack conditions and the limits on stream velocity for acceptable use of each nozzle are also shown. The minimum and maximum velocity variations that may be encountered when using each nozzle are given in the last two columns of the table. The range of velocities bracketed by this nozzle set is 139 to 21 ft/s. The actual minimum velocity ratio, R_{min}, from Figure 2-1, corresponding to the nozzle velocity for the largest nozzle (0.201 in.) is something less than the minimum velocity ratio of 0.5 specified in Table 2-3 (the lower limit of Figure 2-1). Consequently, velocities lower than 21.0 ft/s may be sampled with this nozzle without violating the limits on the anisokinetic sampling error (the aspiration coefficient). It should be noted here that the full range of nozzle diameters will not be required in most instances. In other words, sampling situations will seldom be encountered which require the smallest or largest nozzle diameters shown in the table.

Because of the impact the nozzle geometry may have on performance of the $PM_{2.5}$ device, specification of nozzle inlet diameter is not sufficient to guarantee acceptability. Numerous laboratory tests have resulted in the development of the nozzle design shown in Figure 2-5. The flange and exit geometry were designed to mate with the inlet of Cyclone IV as designed for use in the SRI/EPA Five-Stage Series Cyclone. The critical geometric parameters shown in the figure are specified in Table 2-4 for the nozzle diameters discussed previously. The optimum inside taper or cone angle, θ, was determined from laboratory tests. The outside taper, ϕ, should be 15°, and the inlets should have sharp edges so that the criteria of Belyaev and Levin (1972) for negligible particle bounce from the inlet will be met. The length of the straight section at the nozzle inlet, ℓ, should not exceed 0.05 in. Longer inlet sections may result in the development of velocity profiles in the nozzle, which may seriously perturb performance of the device or contribute to excessive particle losses in the nozzle. The minimum total length of the nozzles should be 1.45 in. This length was chosen to position the nozzle inlet a sufficient distance away so that the body of the sampler would not disrupt the flow. This requires a straight section at the nozzle outlet (after the inside expansion from the inlet diameter) ranging in length from 0.16 to 1.08 in. for the nozzle diameters shown in Table 2-3.

TABLE 2-3. $PM_{2.5}$ NOZZLE DIAMETERS AND VELOCITY LIMITS

Nozzle Diameter (in.)	Nozzle Velocity (ft/s)	Min. Stream vel. A-0.8 (ft/s)	Min. vel. ratio (R_{min})	Max. Stream vel. A-1.2 (ft/s)	Max. vel. ratio (Rmax)	Stream vel. between limits (ft/s)	Min. vel. var. (+/-)	Max. vel. var. (+/-)
0.125	108.6	62.9	0.58	139.0	1.28	--	--	0.35
0.138	89.8	44.9	0.50	119.5	1.33	91.2	0.31	0.42
0.156	69.5	34.7	0.50	98.8	1.42	71.8	0.38	0.46
0.172	57.4	28.7	0.50	86.1	1.50	60.4	0.43	0.50
0.188	48.3	24.1	0.50	72.4	1.50	50.6	0.43	0.50
0.201	42.1	21.0	0.50	63.1	1.50	43.6	0.45	0.50

Note: These calculations are based on the following dry gas composition (percent volume) and water fraction:

N_2	O_2	CO_2	CO	H_2O
79	4	16	1	0.06

Gas conditions are assumed to be (°R, in. H_2O, and in. Hg):

T	ΔP	P_{bar}
760	-2	29.5

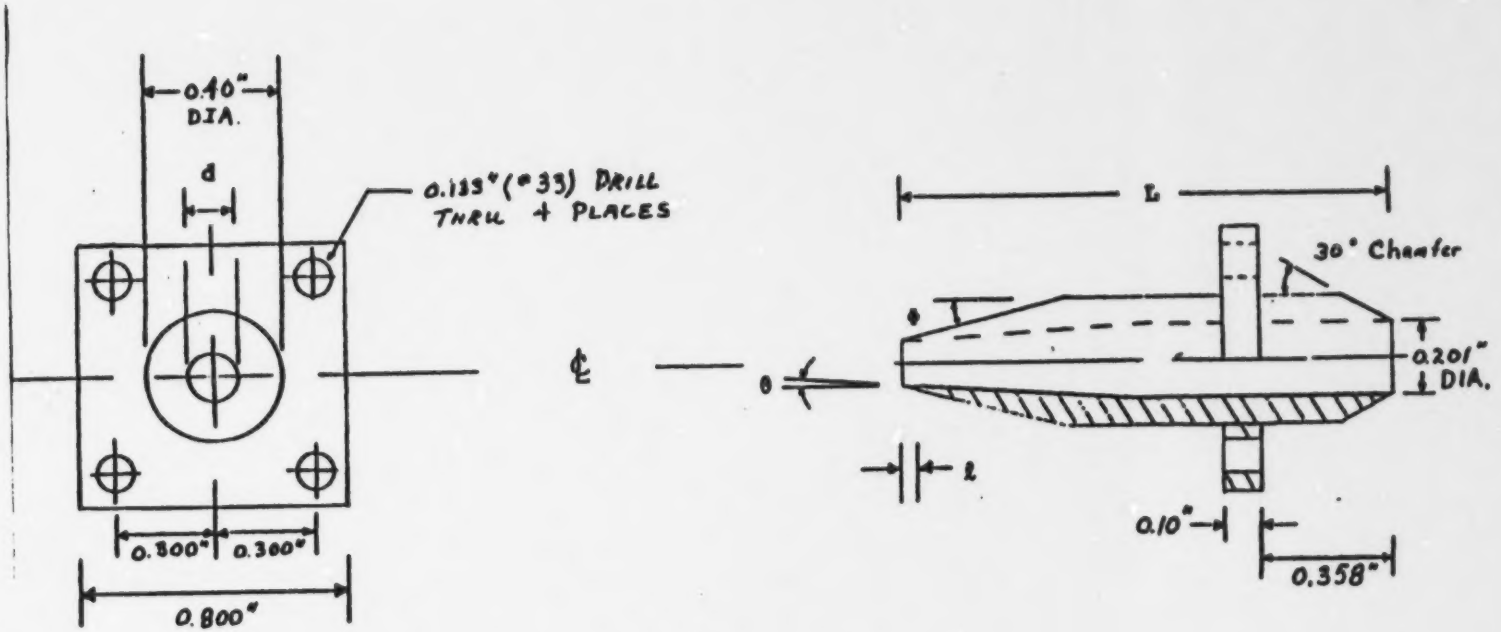


Figure 2-5. $PM_{2.5}$ nozzle design.

TABLE 2-4. $PM_{2.5}$ NOZZLE GEOMETRIES

Nozzle Diameter (in.)	Cone Angle, θ (degrees)	Outside Taper, θ (degrees)	Straight Inlet Length, @ (in.)	Total Length, L (in.)
0.125	3	15	≥0.05	1.45 ±0.05
0.138	2	15	≥0.05	1.45 ±0.05
0.156	1	15	≥0.05	1.45 ±0.05
0.172	1	15	≥0.05	1.45 ±0.05
0.188	1	15	≥0.05	1.45 ±0.05
0.200	0	15	≥0.05	1.45 ±0.05

SECTION 3

CALIBRATION

Calibration procedures for a sampling system are the same whether performing PM_{10} or $PM_{2.5}$. Complete procedures are outlined in the CSR or EGR operator's manual and will not be repeated here (see Farthing and Dawes). For the CSR manual, see Farthing and Dawes in the References at the end of this report. For the EGR manual, see Martin, Dawes, et al., in the Reference section.

SECTION 4

PRESAMPLING ACTIVITIES

Presampling activities for a CSR or EGR sampling system include equipment calibration or operation checks and preparation of sampling reagents. These procedures are fully described in the operator's manual for PM_{10}. No change is necessary for $PM_{2.5}$.

SECTION 5A

SAMPLING PARAMETERS: $PM_{2.5}$ ONLY

The basic principles of CSR operation (constant sample flow rate and dwell time proportional to local stack velocity) are the same for measuring either PM_{10} or $PM_{2.5}$. However, there are some changes in calculation of the setup parameters when the method is being used for the measurement of $PM_{2.5}$. For the sake of a unified presentation, all calculations required to determine the sampling parameters for $PM_{2.5}$ will be given here and not just those which have been changed.

PRELIMINARY SETUP PARAMETERS

Traverse Points

Before the appropriate sampling parameters can be calculated, some preliminary determinations must be made. First, the number of traverse points required for CSR should be determined from Figure 5A-1, based on the distance measured in duct diameters) upstream or downstream from the nearest flow disturbance to the measurement site. For a rectangular stack, an equivalent duct diameter should be calculated as in Method 1. These traverse points should be located within the duct as described in Method 1.

Stack Gas Temperature, Velocity, and Gas Constituents

When the number of traverse points and their location within the duct has been decided upon, the stack temperature and velocity at each of these points should be determined by Method 2.

The concentration of the primary stack gas constituents (i.e., oxygen, carbon dioxide, nitrogen, carbon monoxide, and water vapor) may be determined from Method 3 and Method 4 data. With this information, the gas dry and wet molecular weights, M_d and M_w, may be determined from the following equations:

$$M_d = 32f_o + 44f_c + 28(1 - f_o - f_c) \qquad (5A\text{-}1)$$

$$M_w = M_d(1 - B_{ws}) + 18B_{ws} \qquad (5A\text{-}2)$$

It may be necessary to perform additional measurements with other methods in instances where the stack gas composition is influenced by gases other than those listed above. For example, when sampling gases from a high-sulfur source, Method 6 should be used to determine the percentage of SO_2 present in the process gas, and this should be taken into account when determining the dry molecular weight.

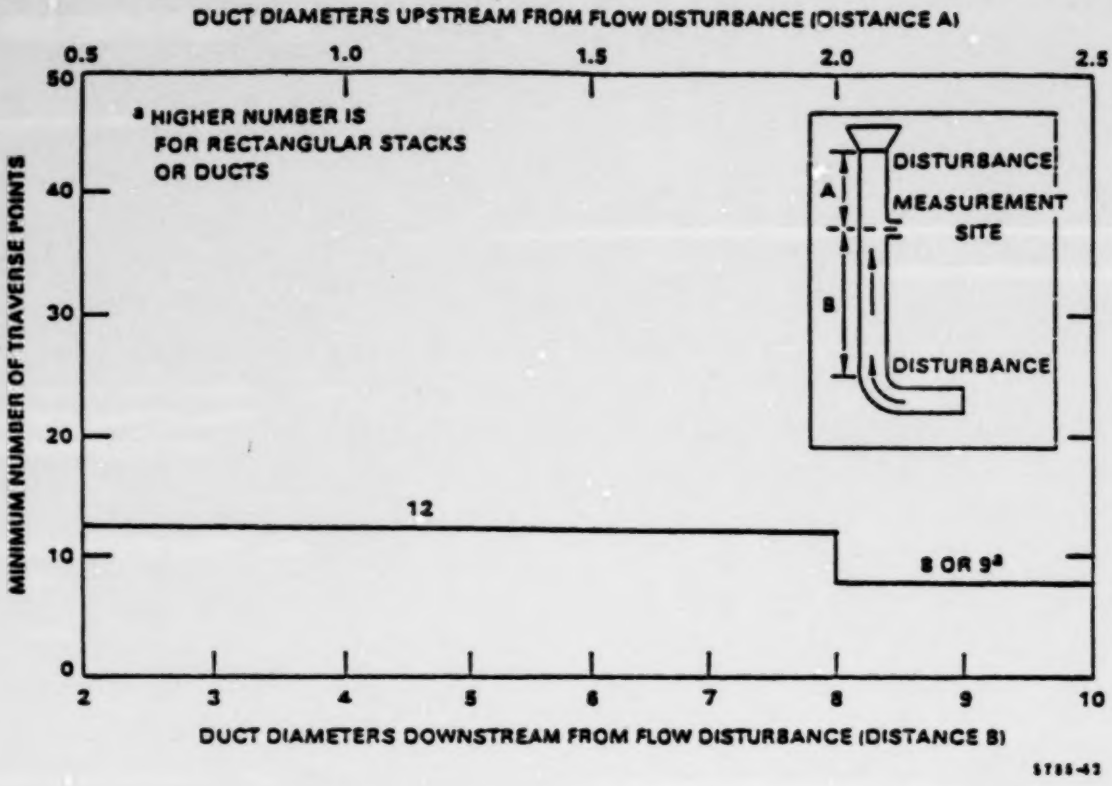


Figure 5A-1. Minimum number of traverse points for CSR traverse.

SETUP CALCULATIONS FOR A SINGLE-STAGE CYCLONE SAMPLER

Sample Flow Rate

If a single-stage cyclone sampler is to be used, the sample flow rate must be that which provides a 2.5 μm size cut. This flow rate will be uniquely determined by the gas composition and temperature of the process gas. The relationship between flow rate and gas parameters specific to the sampling device must be determined by calibration measurements (described in Section 2) before field use. For SRI/EPA Cyclone IV this relationship takes the following form:

$$\ln \sqrt{Stk_{50}} = 29.494 + 2.841(\ln Re) - 18.929(\ln Re)^{1/2} \qquad (5A\text{-}3)$$

where $$Stk_{50} = D_{50}^2 \frac{4CQ}{9\pi\mu d^3} \qquad (2\text{-}4)$$

$$Re = \frac{4\rho Q}{\pi\mu d} \qquad (2\text{-}5)$$

and all variables are as defined previously in Section 2.

Unfortunately, equation 5A-3 cannot be solved in a straightforward manner for flow rate. Therefore, linear regression was used to approximate the curve in equation 5A-3 with two lines. The resulting equation for flow rate when Reynolds number is less than 3162 is:

$$Q_s = (2.7878 \times 10^{-3})\left(\frac{\mu}{C^{0.4241}}\right)\left(\frac{P_s M_w}{T_s}\right)^{-0.5750} \qquad (5A\text{-}4)$$

The flow rate equation for Reynolds number greater than 3162 is:

$$Q_s = (2.4560 \times 10^{-3})\left(\frac{\mu}{C^{0.6205}}\right)\left(\frac{P_s M_w}{T_s}\right)^{-0.3795} \qquad (5A\text{-}5)$$

After the $PM_{2.5}$ flow rate has been determined from either equation 5A-4 or 5A-5, the Reynolds number should be calculated from equation 2-8 to determine the acceptability of the flow rate equation used.

A comparison of the flow rate equation given in Section 5 of the CSR operators manual to obtain a 10 μm cut in SRI/EPA Cyclone I and equations 5A-4 and 5A-5 indicates they are similar with the exception of the Cunningham correction factor. The effect of the Cunningham correction factor is very small with larger particles, and therefore, C is assumed to be 1.0 for PM_{10}. This assumption cannot be made for $PM_{2.5}$, so C must be included in flow rate equations for $PM_{2.5}$.

The Cunningham correction factor is defined by the equation

$$C = 1 + \frac{2\ell}{D_{50}}\left[1.23 + 0.41\exp\left(\frac{-0.44D_{50}}{\ell}\right)\right] \quad (5A\text{-}6)$$

where ℓ is the mean free path of air molecules at stack conditions. For situations in which $D_{50}/\ell > 2.7$, the exponential term can be neglected, so

$$C = 1 + \frac{2.46\ell}{D_{50}} \quad (5A\text{-}7)$$

The mean free path, ℓ (in centimeters), is given by the expression

$$\ell = (2.3249 \times 10^{-6})\left(\frac{\mu}{P_s}\right)\left(\frac{T_s}{M_w}\right)^{1/2} \quad (5A\text{-}8)$$

Substituting into equation 5A-7 for a D_{50} of 2.5 μm, the equation for the Cunningham correction factor becomes

$$C = 1 + (2.2877 \times 10^{-3})\left(\frac{\mu}{P_s}\right)\left(\frac{T_s}{M_w}\right)^{1/2} \quad (5A\text{-}9)$$

The viscosity of the flue gas can be determined by the following equation (Williamson et al., 1983) in which C_1, C_2, C_3, C_4, and C_5 are constants which have no relationship to the Cunningham correction factor, C, as defined above:

$$\mu = C_1 + C_2T_s + C_3T_s^2 + C_4B_{ws} + C_5f_o \quad (5A\text{-}10)$$

where μ is in micropoise, T in degrees Celsius, and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

or for T in degrees Rankine

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147$

This equation fits data (with a standard error of 0.98 μp) for combustion gas of arbitrary composition in the temperature range from 0 to 350°C, 0 to 70% moisture. This equation was generated by SRI personnel from a large data base of viscosities calculated by the more rigorous algorithm of Wilke (1950).

Nozzle Selection

After the sample flow rate has been determined, the corresponding nozzle velocity for any given nozzle may be determined from the following equation:

$$u = \frac{4}{\pi d^2} \cdot Q_s \qquad (5A\text{-}11)$$

where u = nozzle velocity
d = nozzle diameter
Q_s = sample flow rate

For each nozzle velocity, a range of stack velocities, v_{min}, to v_{max} for which the anisokinetic sampling errors are within acceptable limits must then be determined. As discussed in Section 2, this range of stream velocities is governed by the semi-empirical relationship developed by Belyaev and Levin (1974):

$$A = 1 + (R - 1)\frac{B}{B+1} \qquad (2\text{-}3)$$

where A = aspiration coefficient, measured concentration/actual concentration
R = ratio of stream velocity to nozzle velocity, v/u
$B = (2 + 0.617/R)K$
K = particle Stokes number with respect to the nozzle, rv/d
r = particle relaxation time $CD^2/18\mu$
C = Cunningham slip correction factor
D = particle aerodynamic diameter
μ = gas viscosity

Defining v_{min}, as the stack velocity at which A equals 0.9 and v_{max} the stack velocity at which A equals 1.1, we obtain equations for v_{min}, and v_{max} such that

$$v_{min} = u\left[0.2957 + \sqrt{0.3652 - \frac{2.0979 Q_s^{1/2}\mu}{u^{3/2}}}\right] \qquad (5A\text{-}12)$$

$$v_{max} = u\left[0.3957 + \sqrt{0.4960 + \frac{2.0979 Q_s^{1/2}\mu}{u^{3/2}}}\right] \qquad (5A\text{-}13)$$

While the v_{min} and v_{max} for a given nozzle are useful, the local stack velocity is actually measured as velocity pressure differentials during both Method 2 and CSR traverses. Therefore, it is useful to convert v_{min}, and v_{max} to the corresponding pressure differentials, ΔP_{min}, and ΔP_{max}, by using the following equations:

$$\Delta P_{min} = (1.3686 \times 10^{-4}) \left[\frac{P_s M_w}{T_s} \right] \left[\frac{v_{min}}{C_p} \right]^2 \quad (5A\text{-}14)$$

$$\Delta P_{max} = (1.3686 \times 10^{-4}) \left[\frac{P_s M_w}{T_s} \right] \left[\frac{v_{max}}{C_p} \right]^2 \quad (5A\text{-}15)$$

where C_p is the pitot coefficient of the CSR sampling probe and all other variables are as defined previously.

Finally, given the most recent Method 2 data for the sampling plane and the ΔP limits for a given set of nozzles, the nozzle or nozzles required to perform the sample traverse may be determined. It should be noted here that in instances where the pitot coefficients of the Method 2 probe (C'_p) and the CSR probe (C_p) are different, the Method 2 data should be converted to equivalent values for the CSR pitot. This is accomplished by using the following equation:

$$\Delta P_s = \Delta P_H \left[\frac{C_p}{C'_p} \right]^2 \quad (5A\text{-}16)$$

The ΔP limits for the chosen nozzle should bracket those measured. If more than one nozzle is acceptable, the one giving the greatest symmetry should be chosen. Note that if the expected pitot ΔP for one or more points is near a limit for the selected nozzle, it may be outside the limits during a run.

SETUP CALCULATIONS FOR CASCADE IMPACTOR SAMPLERS

Several cascade impactors that are commercially available can be used for measurement of $PM_{2.5}$. The relationships between particle size cut, sample flow rate, gas composition and temperature must have been determined by calibration measurements (described in Section 2) before field use. Procedures for operating these cascade impactors, calculating particle size cut for each stage, and analyzing the results to obtain cumulative mass concentration as a function of particle size are described by McCain et al. (1986).

Sample Flow Rate

The multiple stages of a cascade impactor provide the ability to interpolate, thus permitting determination of $PM_{2.5}$ without the requirement that a particular stage have a 2.5 μm size cut. This flexibility in flow rate permits minimization of error due to anisokinetic sampling by selection of a nozzle and flow rate corresponding to the average stream velocity, v, of the process stream. The sample flow rate is selected from the set Q_n determined by

$$Qn = \frac{\pi d_n^2}{4} \cdot v \quad (5A\text{-}17)$$

One flow rate is selected from the set Q_a subject to the additional criteria that

- Two stage cuts must be equal to or greater than 2.5 μm with two succeeding size cuts below 2.5 μm,
- The separation between these successive size cuts must be no more than a factor of 2 and no less than a factor of 1.5, and
- The product of jet velocity and size cut for each impactor stage with a cut above 2 μm should satisfy the criteria given by McCain et al. (1986) for the particulate collection substrates utilized.

Nozzle Selection

Calculation of minimum and maximum stream velocities, v_{min}, and v_{max}, for a given nozzle depends upon the desired accuracy for particles greater than 2.5 μm. If there is no or little concern for the particulate fraction above 2.5 μm, the calculation of v_{min}, and v_{max} given for single-stage cyclones (equations 5A-12 and 5A-13) and similarly for ΔP_{min} and ΔP_{max} (equations 5A-14 and 5A-15) can be used. The errors in cumulative concentration versus particle size, due to anisokinetic sampling, will be limited to no more than ±10 at 2.5 μm, decreasing sharply with particle size. The corresponding error for $PM_{2.5}$ will be much less, depending upon the particle size distribution below 2.5 μm.

If accurate measurement of particle sizes greater than 2.5 μm is sought, then the more restrictive limits of McCain et al. (1986), which require a nozzle velocity within ±20% of the stream velocity at each traverse point, are recommended. In this instance, the error limit for cumulative percent data can be determined from equation 2-3. The aspiration coefficient, A, can be calculated from this equation as a function of particle size and the average velocity ratio. This result may then be used to correct the impactor data for anisokinetic sampling error.

SAMPLE ORIFICE PRESSURE DROP

After the sample flow rate and nozzle size have been determined, the orifice pressure drop, ΔH, corresponding to this sample flow rate may then be calculated from the following equation:

$$\Delta H = \left[\frac{Q_s (1-B_{ws}) P_s}{T_s} \right]^2 \left[T_M M_d \frac{1.083\ \Delta H@}{P_s} \right] \qquad (5A\text{-}18)$$

DWELL TIME

When sampling with EPA Methods 5 or 17, the dwell time at each traverse point is the same. The measured concentration is a velocity-weighted average for all points, as it should be for determination of emission rate, because the sampling rate is varied at each point proportional to point velocity. Since flow rate cannot be adjusted from point to point with CSR, the dwell

time at each point must be proportional to the point velocity to obtain a velocity-weighted sample.

The dwell time, t_1, for the first sample point is calculated prior to starting the run in the following manner:

$$t_1 = \frac{\sqrt{\Delta P_1}}{(\sqrt{\Delta P})_{avg}} \cdot \frac{t_r}{N} \qquad (5A\text{-}19)$$

where t_r is the projected total sampling time.

At each subsequent traverse point, the velocity ΔP is measured and the new dwell time, t_n, is calculated by using the following equation:

$$t_n = \frac{t_1 \sqrt{\Delta P_n}}{\sqrt{\Delta P_1}} \qquad (5A\text{-}20)$$

It is recommended that t_r for each point be rounded to the nearest 1/4 minute.

The total run time given in equation 5A-19 should be greater than or equal to the minimum total sampling time specified in the test procedures for the specific industry. Further, it is required that (1) the sampling time per point is not less than 2 min (or some greater time interval if specified by the administrator) and (2) the sample volume taken (corrected to standard conditions) will exceed the required minimum total gas sample volume. The expected total volume of gas to be sampled during a single run may be approximated using the sample flow rate and average run time.

In some circumstances, such as batch cycles, it may be necessary to sample for shorter times at the traverse points and to obtain smaller gas sample volumes. In these cases, the approval of the administrator should be obtained.

PERFORMING THE CALCULATIONS

Calculation of the equations presented in the previous subsections may be performed in a number of ways. A set of worksheets to be used for hand calculation of the set up equations has been prepared for SRI/EPA Cyclone IV. These worksheets are shown in Figures 5A-2, 5A-3, and 5A-4.

It should be noted here that if the stack gas temperature changes such that it is outside ±50°F of the average used for the setup calculations, the setup parameters should be recalculated. To save time during the run, it is recommended that these preliminary calculations be performed before sampling for a range of stack temperatures. A table is included in Figure 5A-2 to facilitate these calculations when using the worksheets.

CSR WORKSHEET IA

SAMPLE FLOW RATE AND ORIFICE ΔH
For $PM_{2.5}$

Barometric Pressure, P_a, in. Hg = _____

Stack Differential Pressure, D_p stack, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

Meter Temperature, T_M, °R = _____

Orifice ΔH@, in. H_2O = _____

Gas Analysis:

O_2 fraction, f_o = _____
CO_2 fraction, f_c = _____
Water fraction, B_{ws} = _____

$$M_d = 44f_c + 32f_o + 28(1 - f_o - f_c) = _____$$

$$M_w = M_d(1 - B_{ws}) + 18\,B_{ws} = _____$$

$$P_s = P_a + \frac{D_p \text{ stack}}{13.6} = _____$$

$$\mu = 51.05 + 0.207\,T_s + 3.24 \times 10^{-5}\,T_s^2 + 53.147(f_o) - 74.143(B_{ws}) = _____$$

Figure 5A-2. CSR Worksheet IA - Sample flow rate and orifice ΔH calculations for $PM_{2.5}$.

CYCLONE IV (2.5 μm D_{50})

$$C = 1 + (2.2877 \times 10^{-3})\left(\frac{\mu}{P_s}\right)\left(\frac{T_s}{M_w}\right)^{1/2} = _____$$

$$Q_s = (2.7878 \times 10^{-3})\left(\frac{\mu}{C^{0.4241}}\right)\left(\frac{P_s M_w}{T_s}\right)^{-0.5759}$$

$$= _____ \quad (Re < 3162)$$

or

$$Q_s = (2.4560 \times 10^{-3})\left(\frac{\mu}{C^{0.6205}}\right)\left(\frac{P_s M_w}{T_s}\right)^{-0.3795}$$

$$= _____ \quad (Re > 3162)$$

$$Re = (8.640 \times 10^{5})\ \frac{P_s M_w}{T_s}\ \frac{Q_s}{\mu} = _____$$

Note: Calculate Re to check appropriate flowrate equation used.

$$\Delta H = \left(\frac{Q_s(1 - B_{ws})P_s}{T_s}\right)^2 \left(T_M M_d\ \frac{1.083\ \Delta H@}{P_a}\right) = _____$$

Sample Orifice ΔH for Range of Stack Temperatures

T_s, °R				
T_s, °F				
ΔH, in. H_2O				

Figure 5A-2. Continued

CSR WORKSHEET IIA

NOZZLE SELECTION
For $PM_{2.5}$

Barometric Pressure P_a, in. Hg = _____

Stack Differential Pressure, D_p stack, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

Meter Temperature, T_M, °R = _____

Sample Flowrate, Q_s, acfm = _____

Gas Analysis:

O_2 fraction, f_o = _____
CO_2 fraction, f_c = _____
Water fraction, B_{ws} = _____

SIM-5 Pitot Coefficient, C_p = _____

Method 2 Pitot Coefficient, C_p' = _____

$M_d = 44f_c + 32f_o + 28(1 - f_o - f_c)$ = _____

$M_w = M_d(1 - B_{ws}) + 18(B_{ws})$ = _____

$P_s = P_a + \frac{D_p \text{ stack}}{13.6}$ = _____

$u = 51.05 + 0.207\ T_s + 3.24 \times 10^{-5}\ T_s^2 + 53.147\ (f_o)$

$- 74.143(B_{ws})$ = _____

Nozzle ID				
d_n, inches				
u, fps				
v_{min}, fps				
v_{max}, fps				
ΔP_{min}, in. H_2O				
ΔP_{max}, in. H_2O				

Figure 5A-3. CSR Worksheet IIA - Nozzle selection for $PM_{2.5}$.

$$u = \frac{3.056\ Q_s}{d_n^2}$$

$$v_{min} = u\left[0.2957 + \sqrt{0.3652 - \frac{2.0979\ Q_s^{1/2}\ \mu}{u^{3/2}}}\right]$$

$$v_{max} = u\left[0.3957 + \sqrt{0.4960 + \frac{2.0979\ Q_s^{1/2}\ \mu}{u^{3/2}}}\right]$$

$$\Delta P_{min} = (1.3686 \times 10^{-4})\left(\frac{P_s\ M_w}{T_s}\right)\left(\frac{v_{min}}{C_p}\right)^2$$

$$\Delta P_{max} = (1.3686 \times 10^{-4})\left(\frac{P_s\ M_w}{T_s}\right)\left(\frac{v_{max}}{C_p}\right)^2$$

VELOCITY TRAVERSE DATA:

$$\Delta P_S = \Delta P_M \left(\frac{C_p}{C_p'}\right)^2 = _____$$

	Port_____		Port_____		Port_____		Port_____	
Point #	ΔP	Noz ID	ΔP	Noz ID	ΔP	Noz ID	ΔP	Noz ID
1	____	_____	____	_____	____	_____	____	_____
2	____	_____	____	_____	____	_____	____	_____
3	____	_____	____	_____	____	_____	____	_____
4	____	_____	____	_____	____	_____	____	_____

Figure 5A-3. Continued

CSR WORKSHEET IIIA

DWELL TIME

Total Run time, t_r, minutes = _____

No. Traverse points, N = _____

Previous Method 2 data:

$(\overline{\sqrt{\Delta P}})_{avg}$ = _____

$\overline{\sqrt{\Delta P_1}}$ = _____

DWELL TIME CALCULATION

$$t_1 = \frac{\overline{\sqrt{\Delta P_1}}}{(\overline{\sqrt{\Delta P}})_{avg}} \frac{t_r}{N}$$

$$t_n = \frac{t_1 \sqrt{\Delta P_n}}{\overline{\sqrt{\Delta P_1}}}$$

	Port _____		Port _____		Port _____		Port _____	
Point #	Δp	t	Δp	t	Δp	t	Δp	t
1	_____	_____	_____	_____	_____	_____	_____	_____
2	_____	_____	_____	_____	_____	_____	_____	_____
3	_____	_____	_____	_____	_____	_____	_____	_____
4	_____	_____	_____	_____	_____	_____	_____	_____

Figure 5A-4. CSR Worksheet IIIA - Dwell time calculations.

SYMBOLS FOR SECTION 5A

A	Aspiration coefficient, measured concentration/actual concentration
B	$(2 + 0.617/R)E$
B_{ws}	Water fraction of stack gas
C	Cunningham slip correction factor
C_p	Pitot coefficient for the CSR probe
C'_p	Pitot coefficient for the Method 2 probe
D	Particle aerodynamic diameter
D_{50}	Cyclone cut diameter, μm
d	Nozzle diameter, in.
d_n	Diameter of nozzle n, in.
f_c	CO_2 fraction
f_o	O_2 fraction
K	Particle Stokes number with respect to the nozzle, $\tau v/d_n$
ℓ	The mean free path of air molecules at sampler inlet conditions, cm
M_d	Dry molecular weight of stack gas, lb/mole
M_w	Wet molecular weight of stack gas, lb/mole
N	Number of traverse points
P_a	Ambient pressure, in. Hg
P_s	Absolute stack pressure, in. Hg
Q_s	Sample flow rate, acfm
Q_n	Flow rate for nozzle n at the average stream velocity

R	Ratio of stream velocity to nozzle velocity, v/u
Re	Reynolds number
Stk_{50}	Stokes number for the sampler D_{50}
t_1	Dwell time at the first traverse point, min
T_M	Absolute gas meter temperature, °R
t_n	Dwell time at traverse point, n, min
t_r	Total run time
T_s	Absolute stack gas temperature, °R
u	Nozzle velocity, ft/s
v	Stream velocity, ft/s
v_{max}	Maximum acceptable stack velocity for a given nozzle, ft/s
v_{min}	Minimum acceptable stack velocity for a given nozzle, ft/s min
ΔH	Orifice pressure drop
$\Delta H@$	Orifice pressure differential for a flow rate of 0.75 cfm at standard conditions, in. H_2O
ΔP_{min}	Minimum acceptable velocity pressure differential for a given nozzle, in. H_2O
ΔP_{max}	Maximum acceptable velocity pressure differential for a given nozzle, in. H_2O
ΔP_M	Velocity pressure differential during the Method 2 traverse
ΔP_s	Velocity pressure differential during the CSR traverse
ΔP_1	The velocity ΔP at the first traverse point
$(\sqrt{\Delta P})_{avg}$	The average square root of ΔP from a previous velocity traverse
ΔP_n	Measured velocity ΔP at point n, in. H_2O
τ	Particle relaxation time $CD^2/18\mu$
μ	Gas viscosity, μp (micropoise)

SECTION 5B

SAMPLING PARAMETERS: $PM_{2.5}$ IN CONJUNCTION WITH PM_{10}

The basic principles of system operation for either the CSR or EGR sampling method are unchanged by the addition of $PM_{2.5}$ to PM_{10}. However, experience has shown that, in most situations, the stages of a sampling device will not follow exactly the same scaling laws with respect to changes in cut diameter when changes in operating conditions occur. Consider the performance projections for SRI/EPA Cyclone I and SRI/EPA Cyclone IV in Tables 5B-1 and 5B-2. These tables show projected cyclone D_{50}'s for a range of stack conditions that might typically be encountered (temperatures ranging from 70 to 550°F, pressures from 25 to 30 in. Hg, and moisture content from 10 to 50%, with typical flue gas composition for the bulk gases) From Table 5B-1, it can be seen that if the flow rate through the sampling device is set to provide a D_{50} of 10 μm in Cyclone I, the Cyclone IV D_{50} varies from 2.22 to 2.75 μm for the range of stack conditions given. If the flow rate through the device is set to achieve a D_{50} of 2.5 μm in Cyclone IV for the same range of conditions, the Cyclone I D_{50} varies from 9.41 to 10.8 μm. Consequently, obtaining data for both size fractions that meet the acceptance criteria for both measurements and provide the maximum tolerance for measurement error will require some compromise between these two flow rates.

The acceptance criteria in Section 9 state that the D_{50} in Cyclone I must fall somewhere between 9 and 11 μm. The D_{50} limits for Cyclone IV are 2.25 and 2.75 μm. In other words, the desired flow rate in Cyclone I must fall below Q_9 (the flow rate that produces a 9 μm cut in the cyclone) and above Q_{11} (the flow rate that produces an 11 μm cut in the cyclone). Similarly, for Cyclone IV, the desired flow rate should fall within the range between $Q_{2.25}$ and $Q_{2.75}$. This situation is represented graphically in Figure 5B-1 for a stack pressure of 30 in. Hg, typical combustion air (8% O_2, 10% CO_2, and 82% N_2) with 10% moisture by volume, and a range of stack temperatures. The range of acceptable flow rates for PM_{10} operation is represented by the area between the two lines labeled Q_9 and Q_{11}. The range of flow rates for acceptable $PM_{2.5}$ operation is represented by the area between the lines labeled $Q_{2.25}$ and $Q_{2.75}$. The acceptance criteria for both cyclones are met when the flow rate chosen falls within the intersection of these two ranges, as shown in Figure 5B-1.

Ultimately, it is desirable to look at the limiting flow rates in the same terms as the acceptance criteria. The limiting flow rates, Q_{11} and $Q_{2.25}$, represent specific D_{50}'s in each of the cyclones for a given set of stack conditions. Considering only Cyclone I, the D_{50} corresponding to flow rate Q_{11} is, by definition, 11 μm. The D_{50} in Cyclone I corresponding to the flow rate $Q_{2.25}$ something less than 11 μm but greater than 9 μm. In

TABLE 5-1B. PROJECTED VARIATION OF CYCLONE IV D_{50} TO ACHIEVE A 10 μm D_{50} IN CYCLONE I

Temp, °F	Pres., in. Hg	H_2O, %	Flow Rate, acfm	D_{50} IV, μm
70	30	10	0.40	2.22
140	30	10	0.45	2.30
212	30	10	0.51	2.32
300	30	10	0.58	2.39
400	30	10	0.66	2.45
550	30	10	0.78	2.51
70	30	50	0.37	2.32
550	30	50	0.76	2.66
70	25	10	0.42	2.32
140	25	10	0.48	2.36
300	25	10	0.61	2.47
550	25	10	0.81	2.66
70	25	50	0.39	2.41
550	25	50	0.81	2.75

TABLE 5-2B. PROJECTED VARIATION OF CYCLONE I D_{50} FOR A 2.5 μm D_{50} IN CYCLONE IV

Temp, °F	Pres., in. Hg	H_2O, %	Flow Rate, acfm	D_{50} I, μm
70	30	10	0.36	10.80
140	30	10	0.41	10.70
212	30	10	0.48	10.50
300	30	10	0.55	10.40
400	30	10	0.64	10.20
550	30	10	0.78	9.96
70	30	50	0.35	10.50
550	30	50	0.80	9.68
70	25	10	0.39	10.60
140	25	10	0.45	10.40
300	25	10	0.61	10.10
550	25	10	0.85	9.70
70	25	50	0.38	10.30
550	25	50	0.88	9.41

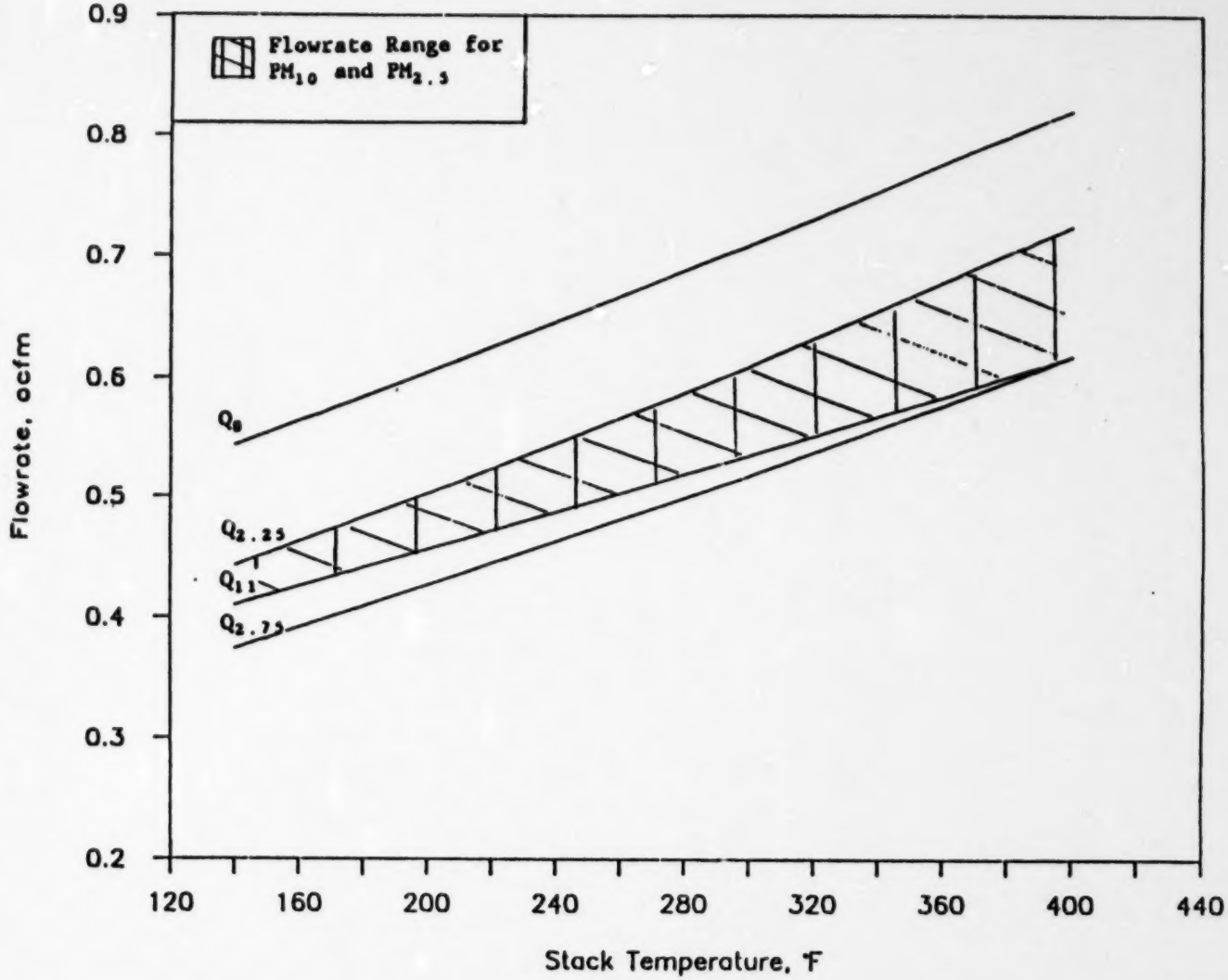


Figure 5B-1. Flow rate range for acceptable PM_{10} and $PM_{2.5}$ sampling.

other words, it can be seen that the addition of $PM_{2.5}$ to PM_{10} reduces the range of acceptable D_{50}'s in Cyclone I by removing the lower portion of the 9 to 11 μm PM_{10} range.

The tolerance, or percent measurement error for which the acceptance criteria will still be met, is given by the ratio of the limiting flow rates. For PM_{10}, the limiting flow rates are Q_9 and Q_{11}. The ratio of these flow rates yields a tolerance of 32.7%, independent of stack conditions. For $PM_{2.5}$, the tolerance is found to be dependent on the cyclone inlet Reynolds number. The ratio of the limiting flow rates ($Q_{2.25}$ and $Q_{2.75}$) is 18.6% for a Reynolds number less than 3162 and 28.3% for a Reynolds number greater than 3162. The tolerance for PM_{10} in conjunction with $PM_{2.5}$ is given by the ratio of $Q_{2.25}$ and Q_{11}. The ratio of these two flow rates gives the following equation for tolerance, which is dependent on stack conditions and the Cunningham slip correction factor for 2.25 μm particles:

$$\frac{Q_{2.25}}{Q_{11}} = 1.229\left[\frac{1}{C_{2.25}}\right]^{0.4241}\left[\frac{T_s}{M_w P_s}\right]^{0.2810} \qquad (5B\text{-}1)$$

The tolerance that may be anticipated for the range of stack conditions given previously in Tables 5B-1 and 5B-2 is shown in Figure 5B-2. The x-coordinates for typical stack conditions, shown in the upper left corner of the figure, allow flow rate tolerances of 13.5 to 20%. It should be noted here that the tolerance, as a function of the Cunningham factor, C, is also a slight function of viscosity and stack pressure in the form $\mu\sqrt{P_s}$. The curve in Figure 5B-2 was plotted for a representative value of $\mu\sqrt{P_s}$ (viscosity of 223.92 μp and stack pressure of 29.5 in. Hg). The minimum and maximum values for this term for the range of stack conditions given in Tables 5B-1 and 5B-2 would result in curves parallel to that in Figure 5B-2 and within a range of ±2%.

A number of approaches may be used to choose a flow rate within the limits of $Q_{2.25}$ and Q_{11}, that would maximize the allowable tolerance. The approach chosen for this manual and presented in the remainder of this section translates the limiting flow rates into the corresponding Cyclone I D_{50}'s, chooses a D_{50} within the calculated range, and converts the chosen D_{50} into the corresponding flow rate. This approach will be presented for both CSR and EGR setup calculations.

PRELIMINARY SETUP PARAMETERS

Traverse Points

Before the appropriate sampling parameters can be calculated, some preliminary determinations must be made. First, the number of traverse points required should be determined. For EGR, this should be done as outlined in Method 1. For CSR, this may be determined from Figure 5B-3. For rectangular stacks, the equivalent duct diameter should be calculated as in Method 1. These traverse points should be located within the duct as described in Method 1.

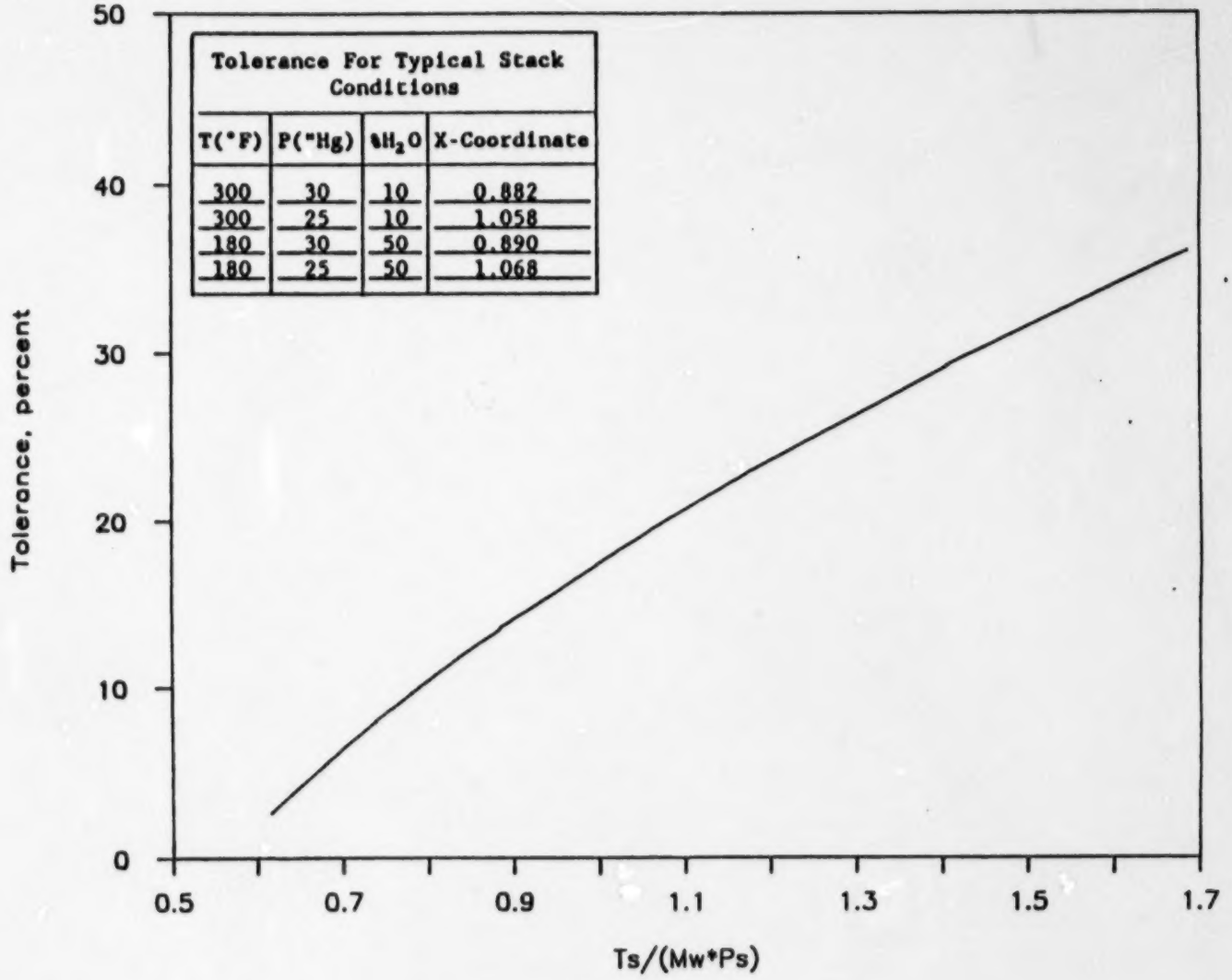


Figure 5B-2. Measurement tolerance as a function of stack conditions.

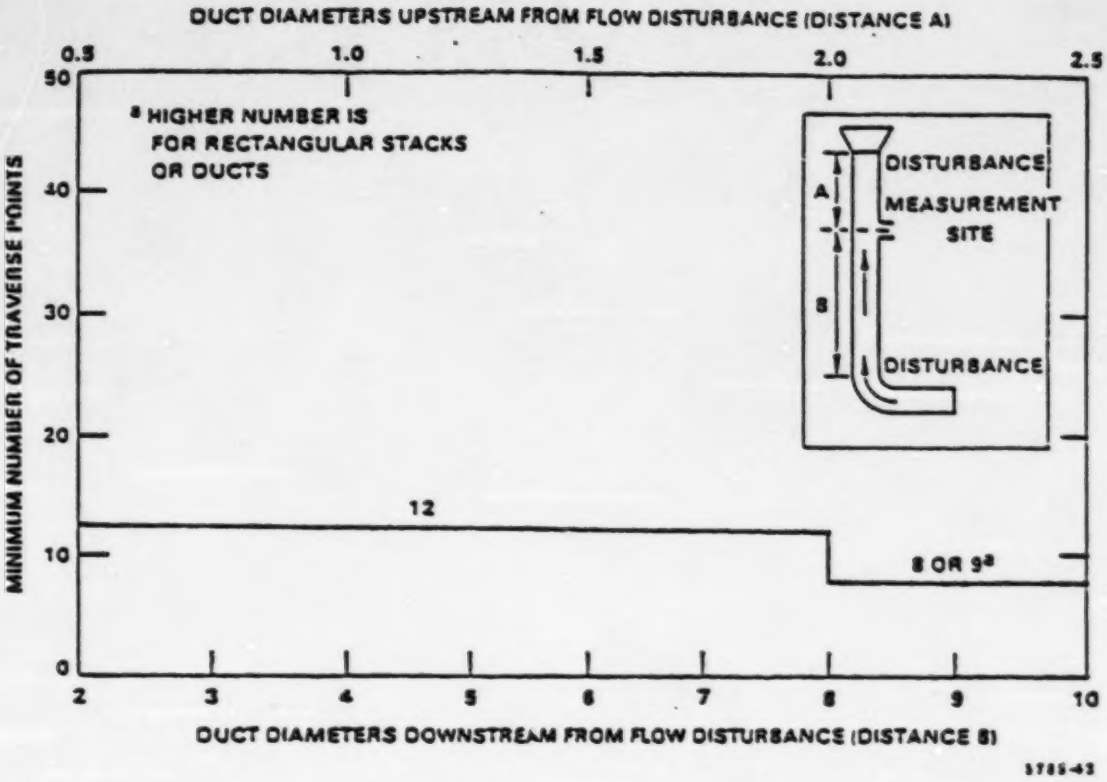


Figure 5B-3. Minimum number of traverse points for CSR.

Stack Gas Temperature, Velocity, and Gas Constituents

When the number of traverse points and their location within the duct has been decided upon, the stack temperature and velocity at each of these points should be determined by Method 2.

The concentration of the primary stack gas constituents (i.e., oxygen, carbon dioxide, nitrogen, carbon monoxide, and water vapor) may be determined from Method 3 and Method 4 data. With this information, the gas dry and wet molecular weights may be determined from the following equations:

$$M_d = 32f_o + 44f_c + 28(1 - f_o - f_c) \quad (5B\text{-}2)$$

$$M_w = M_d(1 - B_{ws}) + 18B_{ws} \quad (5B\text{-}3)$$

It may be necessary to perform additional methods in instances where the stack gas composition is influenced by gases other than those listed above. For example, when sampling gases from a high sulfur source, Method 6 should be performed to determine the percentage of SO_2 present in the process gas, and this should be taken into account when determining the dry molecular weight.

CSR SETUP CALCULATIONS

Sample Flow Rate Selection for a Two-Stage Cyclone Sampler

The flow rate relationship for SRI/EPA Cyclone I is defined by the following equation:

$$Q_I = 0.07296\left(\frac{M_w P_s}{T_s}\right)^{-0.2940}\left(\frac{1}{D_{50}}\right)^{1.4102}(\mu) \quad (5B\text{-}4)$$

For SRI/EPA Cyclone IV, in situations where the inlet Reynolds number is less than 3162, equation 5B-4 has the following form:

$$Q_{IV} = (6.0639 \times 10^{-3})\left(\frac{\mu}{C^{0.4241}}\right)\left(\frac{P_s M_w}{T_s}\right)^{-0.5750}\left(\frac{1}{D_{50}}\right)^{0.8481} \quad (5B\text{-}5)$$

where C is the Cunningham slip correction factor, Q_{IV} is the Cyclone IV flow rate, and all other terms are as defined previously.

For an inlet Reynolds number greater than 3162, the equation becomes:

$$Q_{IV} = (7.6570 \times 10^{-3})\left(\frac{\mu}{C^{0.8205}}\right)\left(\frac{P_s M_w}{T_s}\right)^{-0.3705}\left(\frac{1}{D_{50}}\right)^{1.2410} \quad (5B\text{-}6)$$

The Cunningham slip correction factor, C, appears in both equations 5B-5 and 5B-6 Cyclone IV flow rate) but not in equation 5B-4 Cyclone I flow rate). The larger diameter particles associated with Cyclone I allow the assumption to be made that C is approximately equal to 1.00 in equation 5B-4. However, this does not hold true for the smaller particles of Cyclone IV, so C must be calculated from the following equation:

$$C = 1 + \frac{2\ell}{D_{50}}\left[1.23 + 0.41\exp\left(\frac{-0.44D_{50}}{\ell}\right)\right] \quad (5B\text{-}7)$$

where ℓ is the mean free path of air molecules at inlet conditions. For situations in which $D_{50}/\ell > 2.7$, the exponential term may be disregarded and the equation becomes

$$C = 1 + \frac{2.46\ell}{D_{50}} \quad (5B\text{-}8)$$

The mean free path, ℓ, may be calculated as a function of gas conditions from the following equation:

$$\ell = (2.3249 \times 10^{-7})\left(\frac{\mu}{P_s}\right)\left(\frac{T_s}{M_w}\right)^{1/2} \quad (5B\text{-}9)$$

Substituting into equation 5B-10, the equation for Cunningham slip correction factor becomes

$$C = 1 + (5.7193 \times 10^{-3})\left(\frac{\mu}{D_{50}P_s}\right)\left(\frac{T_s}{M_w}\right)^{1/2} \quad (5B\text{-}10)$$

The viscosity of the flue gas can be determined by the following equation (Williamson et al., 1983):

$$\mu = C_1 + C_2T_s + C_3T_s^2 + C_4B_{ws} + C_5f_o \quad (5B\text{-}11)$$

where μ is in micropoise, T in degrees Celsius, and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

or for T in degrees Rankine

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147$

This equation fits data (with a standard error of 0.98 μp) for combustion gas of arbitrary composition in the temperature range from 0 to 350°C, with 0 to 70% moisture. This equation was generated by SRI personnel from a large data base of viscosities calculated by the more rigorous algorithm of Wilke (1950).

The limiting flow rates for acceptable PM_{10} and $PM_{2.5}$ operation were determined previously to be Q_{11} and $Q_{2.25}$. The D_{50} in Cyclone I corresponding to Q_{11} is, by definition, 11 μm. The Cyclone I D_{50} corresponding to

$Q_{2.25}$, the lower limit for the acceptable range of D_{50} values may be determined from the following equation:

$$D_{50}ll = 9.507\ C^{0.3007}\ \left(\frac{M_w P_s}{T_s}\right)^{0.1883} \qquad (5B\text{-}12)$$

for Cyclone IV, with an inlet Reynolds number less than 3162 where

$D_{50}ll$ = Cyclone I D_{50} corresponding to $Q_{2.25}$
C = Cunningham slip correction factor for a 2.25 μm particle

and all other terms are as defined previously. For situations in which the inlet Reynolds number of Cyclone IV is greater than 3162, the following equation applies:

$$D_{50}ll = 10.0959\ C^{0.4400}\left(\frac{M_w P_s}{T_s}\right) \qquad (5B\text{-}13)$$

where all terms are as defined above.

To maximize the tolerance for measurement error and source fluctuations, the D_{50} chosen for operation should be in the middle of the allowed range

$$D_{50} = \frac{11 + D_{50}ll}{2} \qquad (5B\text{-}14)$$

Finally, the sample flow rate corresponding to this D_{50} must be calculated using the governing relationship for Cyclone I:

$$Q_s = 0.07296\left[\frac{M_w P_s}{T_s}\right]^{-0.2848}\left[\frac{1}{D_{50}}\right]^{1.4102}(\mu) \qquad (5B\text{-}15)$$

Nozzle Selection for a Two-Stage Cyclone Sampler

After the sample flow rate has been determined, the corresponding nozzle velocity for any given nozzle may be determined from the following equation:

$$u = \frac{4Q_s}{\pi d^2} \qquad (5B\text{-}16)$$

where u = nozzle velocity
d = nozzle diameter

For each nozzle velocity, a range of stack velocities, v_{min} to v_{max}, for which the anisokinetic sampling errors are within acceptable limits meet then be determined. As discussed in Section 2, this range of stream velocities is governed by the semi-empirical relationship developed by Belyaev and Levin (1974):

$$A = 1 + (R - 1)\frac{B}{B + 1} \qquad (2\text{-}3)$$

where: A = aspiration coefficient measured concentration/actual concentration
R = ratio of stream velocity to nozzle velocity, v/u
B = (2 + 0.617/R)K
K = particle Stokes number with respect to the nozzle, $\tau v/d$
τ = particle relaxation time $CD^2/18\mu$
C = Cunningham slip correction factor
D = particle aerodynamic diameter
μ = gas viscosity

Defining v_{min} as the stack velocity at which the aspiration coefficient, A, equals 0.8 and v_{max} the stack velocity at which A equals 1.2, we obtain equations for v_{min} and v_{max} such that:

$$v_{min} = u\left[0.2457 + \sqrt{0.3072 - \frac{0.2603\mu\, Q_s^{1/2}}{u^{3/2}}}\right] \qquad (5B\text{-}17)$$

$$v_{max} = u\left[0.4457 + \sqrt{0.5690 + \frac{0.2603\mu\, Q_s^{1/2}}{u^{3/2}}}\right] \qquad (5B\text{-}18)$$

It should be noted that the velocity limits calculated in equations 5B-15 and 5B-18 correspond to the limits on A set for PM_{10} in the CSR operator's manual and not the limits for $PM_{2.5}$ as described in Section 2 of this manual. The PM_{10} limits on stream velocity were chosen as these are more restrictive (as the result of larger particle size).

While the v_{min} and v_{max} for a given nozzle are useful, the local stack velocity is actually measured as velocity pressure differentials, during both Method 2 and CSR traverses. Therefore, it is useful to convert v_{min} and v_{max} to the corresponding pressure differentials, ΔP_{min} and ΔP_{max}, by using the following equations:

$$\Delta P_{min} = (1.3686 \times 10^{-4})\frac{P_s M_w}{T_s}\left[\frac{v_{min}}{C_p}\right]^2 \qquad (5B\text{-}19)$$

$$\Delta P_{max} = (1.3686 \times 10^{-4})\frac{P_s M_w}{T_s}\left[\frac{v_{max}}{C_p}\right]^2 \qquad (5B\text{-}20)$$

where C_p is the pilot coefficient of the CSR sampling probe and all other variables are as defined previously.

Finally, given the most recent Method 2 data for the sampling plane and the ΔP limits for a given set of nozzles, the nozzle or nozzles required to perform the sample traverse may be determined. It should be noted here that in instances where the pitot coefficients of the Method 2 probe (C'_p) and the

CSR probe (C_p) are different, the Method 2 data should be converted to equivalent values for the CSR pitot. This is accomplished using the following equation:

$$\Delta P_s = \Delta P_M \left(\frac{C_p}{C'_p}\right)^2 \qquad \text{(5B-21)}$$

The ΔP limits for the chosen nozzle should bracket those measured. If more than one nozzle is acceptable, choose the one giving the greatest symmetry. Note that if the expected pitot ΔP for one or more points is near a limit for the chosen nozzle, it may be outside the limits during the run.

Sample Flow Rate Selection for Cascade Impactor Samplers

Several cascade impactors that are commercially available can be used for measurement of PM_{10} and $PM_{2.5}$. The relationships between particle size cut, sample flow rate, gas composition, and temperature must have been determined by calibration measurements (described in Section 2) before field use. Procedures for operating these devices, calculating particle size cut for each stage, and analyzing the results to obtain cumulative mass concentration as a function of particle size are described by McCain et al. (1986).

The multiple stages of a cascade impactor provide the ability to interpolate, thus permitting determination of PM_{10} and $PM_{2.5}$ without the problem of flow rate compromises inherent in cyclones. This flexibility in flow rate permits minimization of error due to anisokinetic sampling by selection of a nozzle and flow rate corresponding to the average stream velocity, v, of the process stream. The sample flow rate is selected from the set, Q_n, determined by

$$Q_n = \frac{v\pi d_n^2}{4} \qquad \text{(5B-22)}$$

One set of flow rates should be selected subject to the following additional requirements:

- One stage cut must be equal to or greater than 10 μm with two succeeding size cuts below 10 μm.
- One stage cut must be equal to or greater than 2.5 μm with two succeeding side cuts below 2.5 μm.
- The separation between these successive size cuts must be no more than a factor of 2 and no less than a factor of 1.5.

- The product of jet velocity and size cut for each impactor stage with a cut above 2 μm should satisfy the criteria given by McCain et al. (1986) for the particulate collection substrates utilized.

Nozzle Selection for Cascade Impactor Samplers

The method of calculation of minimum and maximum stream velocities, v_{min} and v_{max}, for a given nozzle depends upon the desired accuracy for particles greater than 10 μm. If there is no or little concern for the particulate fraction above 10 μm, the calculation of v_{min} and v_{max} given for single stage cyclones (equations 5B-15 and 5B-16) and similarly for ΔP_{min} and ΔP_{max} (equations 5B-17 and 5B-18) can be used. The errors in cumulative concentration versus particle size, due to anisokinetic sampling, will be limited to no more than ±20% at 10 μm, decreasing sharply with particle size. The corresponding error for PM_{10} will be much less, depending upon the particle size distribution below 10 μm. The error for $PM_{2.5}$ would be even smaller because of the smaller particle size.

If accurate measurement of particle sizes greater than 10 μm is sought, then the more restrictive limits of McCain et al. (1986), which require a nozzle velocity within ±20% of the stream velocity at each traverse point, are recommended. In this case, the error limit of cumulative percent data for arbitrary size distribution is given by the percent deviation of nozzle velocity from stream velocity.

Sample Orifice Pressure Drop

After the sample flow rate and nozzle size have been determined, the orifice pressure drop, ΔH, corresponding to this sample flow rate may then be calculated from the following equation:

$$\Delta H = \left[\frac{Q_s(1 - B_{ws})P_s}{T_s} \right]^2 \left[T_M M_d \frac{1.083\ \Delta H@}{P_s} \right] \qquad (5B\text{-}23)$$

Dwell Time

When sampling with EPA Method 5 or 17, the dwell time at each traverse point is the same. The measured concentration is a velocity-weighted average for all points, as it should be for determination of emission rate, because the sampling rate is varied at each point proportional to point velocity. Since flow rate cannot be adjusted from point to point with CSR, the dwell time at each point must be proportional to the point velocity to obtain a velocity weighted sample.

The dwell time for the first sample point, t_1, is calculated before starting the run in the following manner:

$$t_1 = \frac{\sqrt{\Delta P_1}}{(\sqrt{\Delta P})_{avg}} \cdot \frac{t_r}{N} \qquad (5B\text{-}24)$$

At each subsequent traverse point where t_r is the projected total sampling time. The velocity ΔP is measured and the new dwell time, t_n, is calculated by using the following equations:

$$t_n = \frac{t_1 \sqrt{\Delta P_n}}{\sqrt{\Delta P_1}} \qquad \text{(5B-25)}$$

It is recommended that t_n for each point be rounded to the nearest 1/4 min.

The total run time given in equation 5B-22 should be greater than or equal to the minimum total sampling time specified in the test procedures for the specific industry. Further, it is required that (1) the sampling time per point is not less than 2 min (or some greater time interval if specified by the administrator), and (2) the sample volume taken (corrected to standard conditions) will exceed the required minimum total gas sample volume. The expected total volume of gas to be sampled during a single run may be approximated by using the sample flow rate and average run time.

In some circumstances, such as batch cycles, it may be necessary to sample for shorter times at the traverse points and to obtain smaller gas sample volumes. In these cases, the approval of the administrator should be obtained.

Worksheets for CSR Setup Calculations

Calculation of the equations presented in the previous subsections may be performed in a number of ways. A set of worksheets to be used for hand calculation of the setup equations has been prepared. These worksheets are shown in Figures 5B-4, 5B-5, and 5B-6.

If the stack gas temperature changes so that it is no longer within ±50°F of the average used for the setup calculations, the setup parameters should be recalculated. To save time during the run, it is recommended that these preliminary calculations be performed before sampling for a range of stack temperatures. A table is included in Figure 5B-4 to facilitate these calculations when using the worksheets.

EGR SETUP CALCULATIONS

Sample Flow Rate Selection for a Two-Stage Cyclone Sampler

The flow rate relationships given previously for Cyclone I and Cyclone IV as equations 5B-4, 5B-5, and 5B-6 still apply when using the EGR method.

CSR WORKSHEET IB

SAMPLE FLOW RATE AND ORIFICE ΔH
For PM_{10} and $PM_{2.5}$.

Barometric Pressure, P_a, in. Hg = _____

Stack Differential Pressure, D_p stack, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

Meter Temperature, T_M, °R = _____

Orifice ΔH@, in. H_2O = _____

Gas Analysis:
O_2 fraction, f_o = _____
CO_2 fraction, f_c = _____
Water fraction, B_{ws} = _____

$$M_d = 44f_c + 32f_o + 28(1 - f_o - f_c) = _____$$

$$M_w = M_d(1 - B_{ws}) + 18(B_{ws}) = _____$$

$$P_s = P_a + \frac{D_p \text{ stack}}{13.6} = _____$$

$$\mu = 51.05 + 0.207\ T_s + 3.24 \times 10^{-5}\ T_s^2 + 53.147\ (f_o)$$

$$- 74.143(B_{ws}) = _____$$

Figure 5B-4. CSR Worksheet IB - Sample flow rate and orifice ΔH calculations for PM_{10} and $PM_{2.5}$.

D_{50} LOWER LIMIT

$$C = 1 + (2.5419 \times 10^{-3})\left(\frac{\mu}{P_s}\right)\left(\frac{T_s}{M_w}\right)^{1/2} = _____$$

$$D_{50LL} = 9.507\, C^{0.3007}\left(\frac{P_s M_w}{T_s}\right)^{0.1993} = _____$$

(for Re <3162)

or

$$D_{50LL} = 10.0959\, C^{0.4400}\left(\frac{P_s M_w}{T_s}\right)^{0.0600} = _____$$

(for Re >3162)

TARGET D_{50}

$$D_{50} = \frac{11 + D_{50LL}}{2} = _____$$

SAMPLE FLOWRATE

$$Q_s = 0.07296\left(\frac{M_w P_s}{T_s}\right)^{-0.2949}\left(\frac{1}{D_{50}}\right)^{1.4102}(\mu) = _____$$

CYCLONE IV INLET REYNOLDS NUMBER

(To check appropriate D_{50LL} equation used)

$$Re = (8.640 \times 10^5)\left(\frac{P_s M_w}{T_s}\right)\left(\frac{Q_s}{\mu}\right) = _____$$

$$\Delta H = \left(\frac{Q_s(1-B_{ws})P_s}{T_s}\right)^2 \left(T_M M_d \frac{1.083\Delta H_e}{P_a}\right) = _____$$

Sample Orifice ΔH for Range of Stack Temperatures

T_s, °R				
T_s, °F				
ΔH, in. H_2O				

Figure 5B-4. (Continued)

CSR WORKSHEET IIB

NOZZLE SELECTION
For PM_{10} and $PM_{2.5}$.

Barometric Pressure P_a, in. Hg = _____

Stack Differential Pressure, D_p stack, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

Meter Temperature, T_M, °R = _____

Sample Flowrate, Q_s, acfm = _____

Gas Analysis:
O_2 fraction, f_o = _____
CO_2 fraction, f_c = _____
Water fraction, B_{ws} = _____

SIM-5 Pitot Coefficient, C_p = _____

Method 2 Pitot Coefficient, C_p' = _____

$M_d = 44f_c + 32f_o + 28(1 - f_o - f_c)$ = _____

$M_w = M_d(1 - B_{ws}) + 18(B_{ws})$ = _____

$P_s = P_a + \frac{D_p \text{ stack}}{13.6}$ = _____

$\mu = 51.05 + 0.207\ T_s + 3.24 \times 10^{-5}\ T_s^2 + 53.147(f_o)$

$- 74.143\ (B_{ws})$ = _____

Nozzle ID				
d_n, inches				
u, fps				
v_{min}, fps				
v_{max}, fps				
ΔP_{min}, in. H_2O				
ΔP_{max}, in. H_2O				

Figure 5B-5. CSR Worksheet II - Nozzle selection for PM_{10} and $PM_{2.5}$.

$$u = \frac{3.056\ Q_s}{d_n^2}$$

$$v_{min} = u\left[0.2457 + \sqrt{0.3072 - \frac{0.2603\ Q_s^{1/2}\ \mu}{u^{3/2}}}\right]$$

$$v_{max} = u\left[0.4457 + \sqrt{0.5690 + \frac{0.2603\ Q_s^{1/2}\ \mu}{u^{3/2}}}\right]$$

$$\Delta P_{min} = (1.3686 \times 10^{-4})\left(\frac{P_s M_w}{T_s}\right)\left(\frac{v_{min}}{C_p}\right)^2$$

$$\Delta P_{max} = (1.3686 \times 10^{-4})\left(\frac{P_s M_w}{T_s}\right)\left(\frac{v_{max}}{C_p}\right)^2$$

VELOCITY TRAVERSE DATA:

$$\Delta P_S = \Delta P_M \left(\frac{C_p}{C_p'}\right)^2 = _____$$

	Port_____		Port_____		Port_____		Port_____	
Point #	ΔP	Noz ID	ΔP	Noz ID	ΔP	Noz ID	ΔP	Noz ID
1	____	_____	____	_____	____	_____	____	_____
2	____	_____	____	_____	____	_____	____	_____
3	____	_____	____	_____	____	_____	____	_____
4	____	_____	____	_____	____	_____	____	_____

Figure 5B-5. (Continued)

Unfortunately, sampling with the EGR concept produces a total flow through the cyclone which is a mix of sample gas (with a known moisture fraction) and recycle gas (dry). This necessitates an iterative solution of the cyclone flow rate equations to determine the desired flow rate. To avoid the necessity of iterations on the equations, an approximate solution of the equations has been developed. This approximation has the following form:

$$Q_t = \frac{Q_d - Q_s(Q_d - Q_w)}{Q_w} \qquad (5B\text{-}26)$$

where Q_t = total flow through the cyclone
Q_d = the sampler flow rate when the total flow is composed entirely of dry recycle gas (100% recycle)
Q_s = isokinetic sample flow rate
Q_w = the sampler flow rate when the total flow is composed entirely of sample gas with a known moisture fraction (0% recycle)

Applying the approximation to the flow rate relationship for Cyclone I results in the equation below:

$$Q_I = Q_d + Q_s \left[1 - \frac{\mu_d}{\mu_w}\left(\frac{M_w}{M_d}\right)^{-0.2949}\right] \qquad (5B\text{-}27)$$

where

$$Q_d = 0.07296 \left(\frac{M_d P_s}{T_s}\right)^{-0.2949} (\mu_d)\left(\frac{1}{D_{50}}\right)^{1.4102}$$

$$Q_s = 0.327 d^2 v_{avs}$$

For Cyclone IV with an inlet Reynolds number less than 3162, the approximation takes the form:

$$Q_{IV} = Q_d + Q_s\left[1 - \frac{\mu_d}{\mu_w}\left(\frac{M_w}{M_d}\right)^{-0.5758}\right] \qquad (5B\text{-}28)$$

where $$Q_d = (6.0639 \times 10^{-3})\left(\frac{\mu_d}{C^{0.4241}}\right)\left(\frac{P_s M_d}{T_s}\right)^{-0.5758}\left(\frac{1}{D_{50}}\right)^{0.8481}$$

For inlet Reynolds number greater than 3162, the approximation becomes:

$$Q_{IV} = Q_d + Q_s\left[1 - \frac{\mu_d}{\mu_w}\left(\frac{M_w}{M_d}\right)^{-0.3705}\right] \qquad (5B\text{-}29)$$

where

$$Q_d = (7.6570 \times 10^{-3})\left(\frac{\mu_d}{C^{0.8205}}\right)\left(\frac{P_s M_d}{T_s}\right)^{-0.3705}\left(\frac{1}{D_{50}}\right)^{1.2410}$$

and all other terms are defined previously.

The gas viscosities in the above equations may be calculated in the following manner:

$$\mu_w = C_1 + C_2 T_s + C_3 T_s^2 + C_4 f_w + C_5 f_O \qquad (5B\text{-}30)$$

and

$$\mu_d = C_1 + C_2 T_s + C_3 T_s^2 + C_5 f_O \qquad (5B\text{-}31)$$

where μ is in micropoise, T in degrees Rankine, and the constants are defined previously for equation 5B-11.

The limiting flow rates for PM_{10} and $PM_{2.5}$ operation were defined previously as Q_{11} and $Q_{2.25}$. The D_{50} in Cyclone I corresponding to Q_{11} is, by definition, 11 μm. The Cyclone I D_{50} corresponding to $Q_{2.25}$, the lower limit for the acceptable range of D_{50}'s, must be calculated. First, the flow rate, $Q_{2.25}$, is calculated from either equation 5B-28 or 5B-29 for a D_{50} of 2.25 μm (the inlet Reynolds number should be calculated to check the appropriate equation was used). This flow rate can then be translated into the corresponding Cyclone I D_{50} from the following equation:

$$D_{50}11 = \frac{0.1562\left(\frac{M_d P_s}{T_s}\right)^{-0.2091} (\mu_d)^{0.7091}}{\left[Q_{2.25} - Q_s\left(1 - \frac{\mu_d}{\mu_w}\left(\frac{M_w}{M_d}\right)^{-0.2848}\right)\right]^{0.7091}} \qquad (5B\text{-}32)$$

To maximize the tolerance for measurement error and source fluctuations, the D_{50} chosen for operation should be in the middle of the allowed range:

$$D_{50} = \frac{11 + D_{50}11}{2} \qquad (5B\text{-}33)$$

Finally, the total flow rate in Cyclone I corresponding to this D_{50} must be calculated by using the approximate equation for Cyclone I:

$$Q_t = Q_d + Q_s\left[1 - \frac{\mu_d}{\mu_w}\left(\frac{M_w}{M_d}\right)^{-0.2848}\right] \qquad (5B\text{-}34)$$

where

$$Q_d = 0.07296\left(\frac{M_d P_s}{T_s}\right)^{-0.2848}\left(\frac{1}{D_{50}}\right)^{1.4102}(\mu_d)$$

and D_{50} is the target cut diameter chosen for Cyclone I in equation 5B-33.

Nozzle Selection for A Two-Stage Cyclone Sampler

Selection of the appropriate nozzle size for EGR sampling requires consideration of the recycle rates anticipated at each traverse point. The chosen nozzle should not require recycle rates less than 10% of the total flow.

The first step in nozzle selection is to determine the flow rate, Q_{11}, from the following equation:

$$Q_{11} = (2.4803 \times 10^{-3}) \left[\frac{M_w P_s}{T_s} \right]^{-0.2949} (\mu) \qquad (5B\text{-}35)$$

The target nozzle diameter, d, may then be calculated (in inches) as shown below:

$$d = 1.74808 \sqrt{\frac{Q_{11}}{v_{max}}} \qquad (5B\text{-}36)$$

Because periodic fluctuations in duct velocity can occur, it is recommended that the velocity used in the above calculation be the maximum expected velocity plus 10%.

Once the target nozzle diameter has been determined, the next smallest available nozzle size should be chosen for sampling. The actual calibrated size of the chosen nozzle should be used for all setup calculations.

Target Pressure Differentials (ΔH, ΔP_t, ΔP_r)

When the desired total flow rate, Q_t, has been determined, the pressure differentials across each of the flow-metering devices must be determined. The pressure drop across the total flow laminar flow element (LFE) for the chosen Q_t and for isokinetic Q_s is given by the following equation:

$$\Delta P_t = \frac{\mu_L}{\mu_{ST}} \left[\frac{1}{S_t} \cdot \frac{P_s}{P_L} \cdot \frac{T_L}{T_s} (Q_t - Q_s f_w) - \frac{W_t}{S_t} \right] \qquad (5B\text{-}37)$$

Similarly, for the recycle LFE,

$$\Delta P_r = \frac{\mu_L}{\mu_{ST}} \left[\frac{1}{S_r} \cdot \frac{P_s}{P_L} \cdot \frac{T_L}{T_s} (Q_t - Q_s) - \frac{W_r}{S_r} \right] \qquad (5B\text{-}38)$$

Substituting the equation for Q_s into each of the above equations and simplifying, the equations for ΔP_t and ΔP_r become

$$\Delta P_t = \frac{K_1 Q_t}{S_t} \cdot \frac{1}{T_s} - \frac{K_1 f_w}{S_t} \left[K_2 \left(\frac{\Delta P_v}{T_s} \right)^{1/2} \right] - \frac{\mu_L}{\mu_{ST}} \cdot \frac{W_t}{S_t} \qquad (5B\text{-}39)$$

$$\Delta P_r = \frac{K_1 Q_t}{S_r} \cdot \frac{1}{T_s} - \frac{K_1}{S_r}\left[K_2\left(\frac{\Delta P_v}{T_s}\right)^{1/2}\right] \cdot \frac{\mu_L}{\mu_{ST}} \cdot \frac{W_r}{S_r} \qquad (5B\text{-}40)$$

where $K_1 = \dfrac{\mu_L P_s T_L}{\mu_{ST} P_L}$

and $K_2 = 27.952\ d^2 C_p \left(\dfrac{1}{P_s M_w}\right)^{1/2}$

The governing equation for orifice ΔH is simply that used in Method 5:

$$\Delta H = 846.72\ d^4 \Delta H_@ C_p\ (1 - f_{H_2O})\ \frac{M_d T_M P_s}{M_w T_s P_b}\ \Delta P_v \qquad (5B\text{-}41)$$

While equations 5B-43, 5B-44, and 5B-45 appear cumbersome to use, several of the terms represented are constants or essentially so over the time span of a sampling traverse. Some preliminary calculations can, therefore, reduce these equations to much simpler functions. These, in turn, can be used by the operator to calculate the target pressure differentials for the flow-metering devices at each traverse point.

The worksheets shown as Figures 5B-7 through 5B-9 were developed for this approach to the EGR setup calculations. The target value for orifice ΔH is obtained in Figure 5B-5 by using the standard Method 5 equation, shown above as 5B-41. The total and recycle flow LFE pressure differentials are determined by using equations 5B-39 and 5B-40. The worksheets evaluate the constants in the equations to obtain simplified equations for ΔH, ΔP_t and ΔP_r of the form

$$\Delta H = A_o \Delta P_v$$

$$\Delta P_t = A_t - B_t \sqrt{\Delta P_v}$$

$$\Delta P_r = A_r - B_r \sqrt{\Delta P_v}$$

It should be noted here that to obtain a function of this type for ΔH, ΔP_t or ΔP_r, stack temperature is assumed constant. Values for ΔH and ΔP_t obtained in this manner were found to agree within ±10% with exact solutions for temperature ranges of ±50°F around the average and stack gas moistures up to 50%.

EGR WORKSHEET IB

Total (Cyclone) Flow Rate for PM_{10} and $PM_{2.5}$

Barometric Pressure, P_a, in. Hg = _____

Stack Differential Pressure, D_p Stack, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

Average Velocity, V_{avg}, ft/s = _____

Meter Temperature, T_M, °R = _____

Gas Analysis:
O_2 fraction, f_o = _____
CO_2 fraction, f_c = _____
Water fraction, B_{ws} = _____

Calibration Data:
Nozzle Diameter, d, in. = _____
Pitot Coefficient, C_p = _____

$M_d = 44f_c + 32f_o + 28(1 - f_o - f_c)$ = _____

$M_w = M_d(1 - B_{ws}) + 18(B_{ws})$ = _____

$P_s = P_a + \frac{D_p \text{ stack}}{13.6}$ = _____

$\mu_d = 51.05 + 0.207T_s + 3.24x10^{-5}T_s^2 + 53.147(f_o)$ = _____

$\mu_w = 51.05 + 0.207T_s + 3.24x10^{-5}T_s^2 + 53.147(f_o) - 74.143(B_{ws})$ = _____

$Q_s = 0.327d^2v_{avg}$ = _____

Figure 5B-7. EGR Worksheet IB - Total (Cyclone) Flow rate for PM_{10} and $PM_{2.5}$.

$Q_{2.25}$

$$C = 1 + (2.5419\times10^{-3})\left(\frac{\mu_w}{P_s}\right)\left(\frac{T_s}{M_w}\right)^{1/2} = _____$$

$$Q_d(2.25) = (3.0484\times10^{-3})\left(\frac{\mu_d}{C^{0.4241}}\right)\left(\frac{P_s M_d}{T_s}\right)^{-0.5759} = _____$$
(for Re<3162)

$$Q_d(2.25) = 2.7990\left(\frac{\mu_d}{C^{0.6205}}\right)\left(\frac{P_s M_d}{T_s}\right)^{-0.3795} = _____$$
(for Re>3162)

$$Q_{2.25} = Q_d + Q_s\left[1 - \left(\frac{\mu_d}{\mu_w}\right)\left(\frac{M_w}{M_d}\right)^{-0.5759}\right] = _____$$
(for Re<3162)

or

$$Q_{2.25} = Q_d + Q_s\left[1 - \left(\frac{\mu_d}{\mu_w}\right)\left(\frac{M_w}{M_d}\right)^{-0.3795}\right] = _____$$
(for Re>3162)

D_{50} Lower Limit

$$D_{50\ell\ell} = \frac{0.1562\left(\frac{M_d P_s}{T_s}\right)^{-0.2091}\mu_d^{0.7091}}{\left[Q_{2.25} - Q_s\left(1 - \left(\frac{\mu_d}{\mu_w}\right)\left(\frac{M_w}{M_d}\right)^{-0.2949}\right)\right]^{0.7091}}$$

$$= _____$$

Target D_{50}

$$D_{50} = \frac{11 + D_{50\ell\ell}}{2} = _____$$

Target Total Flowrate

$$Q_d(D_{50}) = 0.07296\left(\frac{M_d P_s}{T_s}\right)^{-0.2949}\left(\frac{1}{D_{50}}\right)^{1.4102}(\mu_d) = _____$$

$$Q_t = Q_d + Q_s\left[1 - \left(\frac{\mu_d}{\mu_w}\right)\left(\frac{M_w}{M_d}\right)^{-0.2949}\right] = _____$$

Figure 5B-7. (Continued)

EGR WORKSHEET IIB

ORIFICE ΔH FOR PM_{10} AND $PM_{2.5}$

Barometric Pressure P_a, in. Hg = _____

Stack Differential Pressure, D_p stack, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

Meter Temperature, T_M, °R = _____

Gas Analysis:

O_2 fraction, f_o = _____

CO_2 fraction, f_c = _____

Water fraction, B_{ws} = _____

Calibration Data:

Nozzle Diameter, d, in. = _____

Pitot Coefficient, C_p = _____

Orifice $\Delta H@$ = _____

$M_d = 44f_c + 32f_o + 28(1 - f_o - f_c)$ = _____

$M_w = M_d(1 - B_{ws}) + 18(B_{ws})$ = _____

$P_s = P_a + \frac{D_p \text{ stack}}{13.6}$ = _____

$A_o = 846.72\ d^4\ \Delta H@\ C_p^2\ (1 - B_{ws})^2\ \frac{M_d T_M P_s}{M_w T_s P_a}$ = _____

$\Delta H = A_o\ \Delta P_v$

= _____

Figure 5B-8. EGR Worksheet IIB - Orifice ΔH for PM_{10} AND $PM_{2.5}$.

EGR WORKSHEET IIIB

Total Flow LFE ΔP_t and Recycle LFE ΔP_r
For PM_{10} and $PM_{2.5}$.

Barometric Pressure, P_a, in. Hg = _____

Stack Differential Pressure, D_p stack, in. H_2O = _____

Average Stack Temperature, T_s, °R = _____

LFE Temperature, T_L, °R = _____

Total (Cyclone) Flowrate, acfm = _____

Gas Analysis:
O_2 fraction, f_o = _____
CO_2 fraction, f_c = _____
Water fraction, B_{ws} = _____

Calibration Data:
Nozzle Diameter, d, in. = _____
Pitot Coefficient, C_p = _____
S_t = _____ S_r = _____
W_t = _____ W_r = _____

$M_d = 44f_c + 32f_o + 28(1 - f_o - f_c)$ = _____

$M_w = M_d(1 - B_{ws}) + 18(B_{ws})$ = _____

$P_s = P_a + \frac{D_p \text{ stack}}{13.6}$ = _____

$P_L = P_a + 0.59$ = _____

$\mu_L = 51.05 + 0.207\ T_L + 3.2355 \times 10^{-5}\ T_L^2 + 53.147(f_o)$ = _____

$\mu_d = 51.05 + 0.207\ T_s + 3.2355 \times 10^{-5}\ T_s^2 + 53.147(f_o)$ = _____

$K_1 = \frac{\mu_L}{180.1} \frac{P_s}{P_L} T_L$ = _____

$K_2 = 27.952 d^2 C_p \left(\frac{1}{P_s M_w}\right)^{1/2}$ = _____

Figure 5B-9. EGR Worksheet IIIB - Total flow LFE ΔP_t and Recycle LFE ΔP_r for PM_{10} and $PM_{2.5}$.

$$A_t = \frac{K_1 \, Q_t}{S_t \, T_s} - \frac{\mu_L \, W_r}{180.1 \, S_r} = _____$$

$$B_t = \frac{K_1 \, K_2 \, B_{ws}}{S_t \, T_s^{1/2}} = _____$$

$$\Delta P_t = A_t - B_t \sqrt{\Delta P_v} = _____$$

$$A_r = \frac{K_1 \, Q_t}{S_r \, T_s} - \frac{\mu_L \, W_r}{180.1 \, S_r} = _____$$

$$B_r = \frac{K_1 \, K_2}{S_r \, T_s^{1/2}} = _____$$

$$\Delta P_r = A_r - B_r \sqrt{\Delta P_v}$$

Figure 5B-9. (Continued)

SYMBOLS FOR SECTION 5B

A	Aspiration coefficient, measured concentration/actual concentration
B	$(2 + 0.617/R)E$
B_{ws}	Water fraction of stack gas
C	Cunningham slip correction factor
$C_{2.25}$	Cunningham slip correction factor for 2.25 μm particles
C_p	Pitot coefficient for the CSR probe
C'_p	Pitot coefficient for the Method 2 probe
D	Particle aerodynamic diameter
D_{50}	Cyclone cut diameter, μm
D_{MM}	Cyclone I D_{50} corresponding to $Q_{2.25}$
d	Nozzle diameter, in.
d_n	Diameter of nozzle n, in.
f_c	Fraction CO_2
f_o	Fraction O_2
K	Particle Stokes number with respect to the nozzle, $\tau v/d$
ℓ	The mean free path of air molecules at sampler inlet conditions, cm
M_d	Dry molecular weight of stack gas, lb/mole
M_w	Wet molecular weight of stack gas, lb/mole
N	Number of traverse points
P_a	Ambient pressure, in. Hg
P_L	Absolute pressure at LFE inlet, in. Hg
P_s	Absolute stack pressure, in. Hg

Q_c	Total flow through the cyclone
Q_d	The sampler flow rate when the total flow is composed entirely of dry recycle gas (100% recycle)
Q_n	Flow rate for nozzle n at the average stream velocity
Q_s	Target sample flow rate, acfm
Q_t	Total cyclone flow rate, acfm
Q_w	The sampler flow rate when the total flow is composed entirely of sample gas with a known moisture fraction (0% recycle)
$Q_{2.25}$	The flow rate that produces a 2.25 μm cut in Cyclone IV
$Q_{2.75}$	The flow rate that produces a 2.75 μm cut in Cyclone IV
Q_9	The flow rate that produces a 9 μm cut in Cyclone I
Q_{11}	The flow rate that produces a 11 μm cut in Cyclone I
Q_I	Cyclone I flow rate, acfm
Q_{IV}	Cyclone IV flow rate, acfm
R	Ratio of stream velocity to nozzle velocity, v/u
Re	Reynolds number
Stk_{50}	Stokes number for the sampler D_{50}
S_r	Recycle flow LFE calibration constant
S_t	Total flow LFE calibration constant
t_1	Dwell time at the first traverse point, min
T_M	Absolute gas meter temperature, °R
T_L	LFE temperature, °R
t_n	Dwell time at traverse point, n, min
t_r	Total run time
T_s	Absolute stack gas temperature, °R
u	Nozzle velocity, ft/s

v	Stream velocity, ft/s
v_{avg}	Average stack velocity, ft/s
v_{max}	Maximum acceptable stack velocity for a given nozzle, ft/s
v_{min}	Minimum acceptable stack velocity for a given nozzle, ft/s
W_r	Recycle flow LFE calibration constant
W_t	Total flow LFE calibration constant
ΔH	Orifice pressure drop
$\Delta H@$	Orifice pressure differential for a flow rate of 0.75 cfm at standard conditions, in. H_2O
ΔP_{min}	Minimum acceptable pressure differential for a given nozzle, in. H_2O
ΔP_{max}	Maximum acceptable pressure differential for a given nozzle, in. H_2O
P_H	Velocity pressure differential from the Method 2 traverse
ΔP_n	Measured velocity ΔP at point n, in. H_2O
ΔP_r	Pressure drop across the recycle flow LIFE, in. H_2O
ΔP_s	Velocity pressure differential for the CSR traverse, in. H_2O
ΔP_t	Pressure drop across the total flow LFE, in. H_2O
ΔP_1	The velocity ΔP at the first traverse point, in. H_2O
$(\overline{\sqrt{\Delta P}})_{avg}$	The average square root of ΔP from a previous velocity traverse
τ	Particle relaxation time $CD^2/18\mu$
μ	Gas viscosity, μp
μ_d	Stack gas viscosity at 0% moisture
μ_L	Gas viscosity at LFE conditions
μ_{ST}	Gas viscosity at standard conditions, 180.1 μp
μ_w	Stack gas viscosity for a known moisture fraction

SECTION 6

TAKING THE SAMPLE

Assembly, leak testing, and operating procedures for sampling are independent of the size fractions being measured. Therefore, the procedures outlined in Section 6 of the appropriate operator's manual (CSR or EGR) should be used regardless of the sample being extracted (PM_{10}, $PM_{2.5}$ or both PM_{10} and $PM_{2.5}$).

SECTION 7

SAMPLE RETRIEVAL

After the sampling system has cooled to a point where it can be safely handled, the collected sample should be recovered. The sample recovery procedures described here are specifically for SRI/EPA Cyclone I and Cyclone IV. Different sampling devices may have different sample recovery procedures.

RECOVERY OF THE PARTICULATE MASS

Great care is needed during recovery of the collected particles from the sampler to insure that all of the particulate matter is recovered and placed in proper sample containers. The sample can be effectively recovered by using a combination of brushing and washing (McCain et al., 1986).

The first step in recovery of the particulate matter from the nozzle and cyclones is to brush the collected mass into the appropriate foil envelope. A clean no. 7 camel's hair brush or small nylon bristle brush is suggested for this operation. The brushed surfaces should then be rinsed thoroughly with acetone, or similar solvent, to recover any particles that continue to adhere to the sampler. These rinses should be collected in uniquely identified sample containers. The brush used for recovery should also be rinsed into the containers.

The filter should be recovered from the filter holder and returned to the petri dish it was taken from during sampler preparation. Any particulate matter or filter fibers adhering to the filter holder surfaces or rubber O-ring should be brushed onto the surface of the filter. The interior surfaces of the filter holder should then be rinsed with the solvent as described above.

As stated previously, assignment of the collected particulate matter to the correct size fraction is very important. Particulate matter on the inner surfaces of the nozzle, the body, collection cup, and cap of Cyclone I are considered part of the sample collected by the cyclone. Furthermore, any matter brushed or rinsed from the <u>outside</u> of the cyclone exit tube is also considered part of the Cyclone I catch. The PM_{10} fraction consists of particulate matter collected on the inner surface of the "turn-around" on the Cyclone I cap, the <u>inside</u> wall of the exit tube, and all internal surfaces downstream of the Cyclone I exit. Particulate matter collected in the connective tubing between Cyclone I and Cyclone IV, the body, collection cup,

and cap of Cyclone IV should be considered a part of the sample collected by Cyclone IV. Any particulate matter brushed or rinsed from the outside of the exit tube is also part of the Cyclone IV catch. The $PM_{2.5}$ fraction consists of particulate matter collected on the inner surfaces of the exit tube of Cyclone IV, all connective tubing up to the filter, and on the surface of the filter.

Final weights for all particulate samples should be determined on site, before shipment. Recommended procedures are outlined in Section 8.

MOISTURE DETERMINATION

Moisture determination procedures are the same as outlined for PM_{10} in the CSR operator's manual.

SECTION 8

POSTSAMPLING CHECKS

Posttest activities are not affected by the size of the fraction being sampled. The procedures outlined in Section 8 of the appropriate operators manual (CSR or EGR) should be followed.

SECTION 9A

DATA ANALYSIS FOR $PM_{2.5}$ SAMPLING

VELOCITY-WEIGHTED AVERAGES

If the velocity distribution at the sampling plane is such that two or more nozzle sizes are required to complete a traverse or if new setup parameters are required during the run because the stack temperature variation exceeds ±50°F, a velocity-weighted average of the stack temperature and particulate concentration must be calculated. For a generic data term, D, this equation takes the form:

$$\bar{D} = \frac{1}{\theta} \sum_{j=1}^{n} D_j t_j \qquad (9A\text{-}1)$$

For the remainder of this section, the term "run" will refer to that portion of a traverse performed without any component changes.

DRY GAS METER VOLUME

The sample volume measured by the dry gas meter can be corrected to standard conditions (68°F and 29.92 in. Hg) by using the following equation:

$$V_{ms} = (V_m \gamma)\left[\frac{T_{st}}{T_m}\right]\left[\frac{P_a + \frac{\Delta H}{13.6}}{P_{st}}\right]$$

$$= 17.65\,(V_m \gamma)\left[\frac{P_a + \frac{\Delta H}{13.6}}{T_m}\right] \qquad (9A\text{-}2)$$

WATER VAPOR VOLUME

The volume of the water vapor collected from flue gas is calculated as follows:

$$V_{ws} = V_{lc}\left[\frac{\rho_{H_2O}}{M_{H_2O}}\right]\left[\frac{R_u T_{st}}{P_{st}}\right] \qquad (9A\text{-}3)$$

$$= 0.04707\,(V_{lc})$$

PERCENT MOISTURE CONTENT

The moisture content of the stack (or sample) gas is calculated with the following equation:

$$B_{ws} = \frac{V_{ws}}{V_{ms} + V_{ws}} \qquad (9A\text{-}4)$$

STACK GAS MOLECULAR WEIGHT

The stack gas dry and wet molecular weight is calculated by using the following equations:

$$M_d = 32f_o + 44f_c + 28(1 - f_o - f_c) \qquad (5A\text{-}1)$$

$$M_w = M_d(1 - B_{ws}) + 18B_{ws} \qquad (5A\text{-}2)$$

STACK GAS VISCOSITY

The viscosity of the stack gas may be calculated from the following equation Williamson et al. 1983):

$$\mu = C_1 + C_2T_s + C_3T^2_s + C_4B_{ws} + C_5f_o \qquad (5A\text{-}10)$$

where μ is in micropoise, T is degrees Celsius, and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

or for T in degrees Rankine

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147$

SAMPLE FLOW RATE

The sample flow rate, at standard conditions, can be found be using the following equation:

$$Q_{s_{ST}} = \frac{V_{ms}}{\theta} \qquad (9A\text{-}5)$$

However, to calculate the particle cut diameter of the inertial classifier, it is necessary to know the flow rate through the sampler at the actual sampler conditions. This can be accomplished by using the following equation:

$$Q_s = Q_{s_{ST}} \left[\frac{1}{1 - B_{ws}} \right] \left[\frac{T_s}{T_{ST}} \right] \left[\frac{P_{ST}}{P_s} \right]$$

$$= 0.056\, Q_{s_{ST}} \left[\frac{1}{1 - B_{ws}} \right] \left[\frac{T_s}{P_s} \right] \qquad (9A\text{-}6)$$

SAMPLER INLET REYNOLDS NUMBER

The Reynolds number at the inlet to an SRI/EPA Cyclone IV is needed to determine which equation should be used to calculate D_{50}. The inlet Reynold's number may be calculated from the following equation:

$$Re = (8.640 \times 10^{-3}) \frac{P_s M_w}{T_s} \frac{Q_s}{\mu} \qquad (9A\text{-}7)$$

SAMPLER D_{50}

The D_{50} or cut-point of each stage of the chosen particle-sizing device should be calculated for accurate determination of the particle size distribution. The cut-point is primarily a function of the actual flow rate through the sampler and the viscosity and density of the stack gas.

The currently available data concerning calibration of SRI/EPA Cyclone IV shows that for a Reynolds number less than 3162 the behavior is described by the equation

$$D_{50} = (2.4302 \times 10^{-3}) \left(\frac{\mu}{Q_s} \right)^{1.1791} \left(\frac{1}{C} \right)^{0.5} \left[\frac{P_s M_w}{T_s} \right]^{-0.6790} \qquad (9A\text{-}8)$$

For a Reynolds number greater than 3162

$$D_{50} = (1.9723 \times 10^{-2}) \left(\frac{\mu}{Q_s} \right)^{0.8058} \left(\frac{1}{C} \right)^{0.5} \left[\frac{P_s M_w}{T_s} \right]^{-0.3058} \qquad (9A\text{-}9)$$

Unfortunately, the Cunningham slip correction factor, C, is a function of D_{50} as defined by the following equation:

$$C = 1 + (5.7193 \times 10^{-3}) \left(\frac{\mu}{D_{50} P_s} \right) \left[\frac{T_s}{M_w} \right]^{1/2} \qquad (9A\text{-}10)$$

Therefore, an iterative solution of equations 9A-8 (or 9A-9) and 9A-10 becomes necessary. First, an initial estimate of C, (C'), should be made by using equation 9A-10, actual stack conditions, and the target D_{50} (2.5 μm). Next, D'_{50} should be calculated from equation 9A-8 (or 9A-9) by using C'. A new value for C, (C"), should then be calculated by using D'_{50}, and this, in turn, should be used to determine a new D_{50} ($D"_{50}$). The iteration should continue in this manner until D'_{50} and $D"_{50}$ agree to within 1%.

If another inertial sizing device is used in conjunction with CSR, the D_{50}'s for each of the stages should be calculated as described in the vendor-supplied operator's manual.

STACK GAS VELOCITY

The stack gas velocity can be found by using the following equation:

$$v = K_p C_p \sqrt{\Delta P} \left[\frac{T_s}{P_s M_w} \right]^{1/2} \qquad (9A\text{-}11)$$

NOZZLE VELOCITY

The nozzle velocity, constant for a specific nozzle diameter, may be calculated from the following equation:

$$u = \frac{3.056\ Q_s}{d^2} \qquad (9A\text{-}12)$$

NOZZLE ΔP LIMITS

For each nozzle and stack gas temperature range, limits on acceptable velocity pressure differentials, ΔP_{min} and ΔP_{max}, were calculated from equations 5A-14 and 5A-15 of the setup calculations. These limits should be tabulated and checked against the average velocity pressure differential at each traverse point to determine acceptability of the run as described later in this section.

PERCENT ISOKINETIC SAMPLING

The following equation should be used to determine the percentage of isokinetic sampling (I):

$$I = \frac{1.677\ T_s \left[0.00267 \cdot V_{lc} + \frac{V_m \gamma}{T_m} \left[P_s + \frac{\Delta H}{13.6} \right] \right]}{\theta v P_s A_n} \qquad (9A\text{-}13)$$

CONCENTRATION

The concentration of the particulate matter caught by each stage can be calculated with the equation below:

$$C'_s = 0.0154\left[\frac{M_p}{V_{ms}}\right] \qquad (9A\text{-}14)$$

The units of grains per standard cubic foot can be converted to milligrams per dry normal cubic meter, mg/dNm^3, by using the following equation:

$$C_s = 2293.2\ C'_s \qquad (9A\text{-}15)$$

ACCEPTANCE CRITERIA

To be acceptable, each run must meet the following criteria:

1) If the percent isokinetic falls within 100±10%, the velocity at one point may be outside the limits for the nozzle; otherwise, the velocity at each traverse point must be within the velocity limits for the nozzle.

2) For single-stage $PM_{2.5}$ samplers

   • D_{50} must be 2.5 ± 0.25 μm

   For multiple-stage $PM_{2.5}$ samplers

   • One stage cut must be equal to or greater than 2.5 μm with two succeeding size cuts below 2.5 μm.

   • Separation between successive size cuts must be no more than a factor of 2 and no less than a factor of 1.5.

   • The product of jet velocity and size cut for each stage with a cut above 2 μm should satisfy the criteria given by McCain et al. (1986).

SYMBOLS FOR SECTION 9A

A_n	Cross-sectional area of sampling nozzle, ft^2
B_{ws}	Proportion by volume of water vapor in the gas stream, dimensionless
C	Cunningham slip correction factor
C_m	Concentration of particulate matter, mg/dNm^3
C'_m	Concentration of particulate matter, gr/dscf
C_p	Pitot tube coefficient, dimensionless
$\overline{D}$	The velocity-weighted average of D
D_j	Average value of D for each nozzle size
D_{50}	Diameter of particles having a 50% probability of penetration, μm
d	Nozzle inlet diameter, in.
f_c	CO_2 fraction
f_o	O_2 fraction
I	Percent isokinetic sampling
K_p	85.48 ft/s(lb/mole-°R)
M_{H_2O}	Molecular weight of water, 18 lb/mole
M_d	Dry molecular weight of stack gas, lb/mole
M_p	Mass of collected particulate (either per stage or total), mg
M_w	Wet molecular weight of stack gas, lb/mole
n	Number of components changes
P_a	Ambient pressure, in. Hg
P_s	Absolute stack pressure, in. Hg
P_{ST}	Absolute pressure at standard conditions, 29.92 in. Hg

Q_s	Flow rate through the sampler (sampler conditions, wet), acfm
$Q_{s_{ST}}$	Sample flow rate (standard conditions), ft^3/min
Re	Reynolds number
R_u	Ideal gas constant, 21.83 in. Hg-ft^3/mole-°R
t_j	Run time for each nozzle size, min
T_m	Average gas meter temperature, °R
T_{ST}	Absolute temperature at standard conditions, 528 °R
T_s	Absolute stack temperature, °R
u	Nozzle velocity, ft/s
v	Stack gas velocity, ft/s
V_{lc}	Total volume of liquid collected in impingers or condenser/silica gel, ml
V_m	Volume of gas sample flow through the dry gas meter (meter conditions), ft^3
V_{MS}	Volume of gas sample flow through the dry gas meter (standard conditions), ft^3
V_{WS}	Volume of water vapor in the gas sample (standard conditions), ft^3
ΔH	Average pressure drop across the orifice, in. H_2O
Δ_p	Velocity pressure head, in. H_2O
ρ_{H_2O}	Density of water, 1 g/ml
θ	Total run time, min
μ	Stack gas viscosity, μp
γ	Gas meter calibration constant
13.6	Specific gravity of mercury

SECTION 9B

DATA ANALYSIS FOR $PM_{2.5}$ AND PM_{10} SAMPLING

Data analysis for simultaneous $PM_{2.5}$ and PM_{10} sampling is dependent on the sampling technique chosen. The data reduction procedures for CSR and EGR, while similar in most instances, do have some significant differences. To avoid confusion, the equations required to perform the data analysis will be given completely and separately for each technique in the same manner as the setup equations in Section 5B. While this does result in some duplication of text and/or equations, a more unified presentation is achieved as a result.

DATA ANALYSIS FOR CSR

Velocity-Weighted Averages

If the velocity distribution at the sampling plane is such that two or more nozzle sizes are required to complete a traverse or if new setup parameters are required during the run because the stack temperature variation exceeds ±50°F, a velocity-weighted average of the stack temperature and particulate concentration must be calculated. For a generic data term, D, this equation takes the form:

$$\bar{D} = \frac{1}{\theta} \sum_{j=1}^{n} D_j t_j \qquad (9B\text{-}1)$$

For the remainder of this section, the term "run" will refer to that portion of a traverse performed without any component changes.

Dry Gas Meter Volume

The sample volume measured by the dry gas meter can be corrected to standard conditions (68°F and 29.92 in. Hg) by using the following equation:

$$V_{MS} = (V_m Y)\left[\frac{T_{ST}}{T_m}\right]\left[\frac{P_a + \frac{\Delta H}{13.6}}{P_{ST}}\right]$$

$$= 17.65\,(V_m Y)\left[\frac{P_a + \frac{\Delta H}{13.6}}{T_m}\right] \qquad (9B\text{-}2)$$

Water Vapor Volume

The volume of the water vapor collected from flue gas is calculated as follows:

$$V_{WS} = V_{lc}\left[\frac{\rho_{H_2O}}{M_{H_2O}}\right]\left[\frac{R_u T_{ST}}{P_{ST}}\right] \qquad (9B\text{-}3)$$

$$= 0.04707\ (V_{lc})$$

Percent Moisture Content

The moisture content of the stack (or sample) gas is calculated by the equation:

$$B_{ws} = \frac{V_{WS}}{V_{HS} + V_{WS}} \qquad (9B\text{-}4)$$

Stack Gas Molecular Weight

The stack gas dry and wet molecular weight is calculated from the following equations:

$$M_d = 32f_o + 44f_c + 28(1 - f_o - f_c) \qquad (5B\text{-}1)$$

$$M_w = M_d(1 - B_{ws}) + 18B_{ws} \qquad (5B\text{-}2)$$

Stack Gas Viscosity

The viscosity of the stack gas, μ, may be calculated from the following equation (Williamson et al., 1983):

$$\mu = C_1 + C_2T_s + C_3T_s^2 + C_4B_{ws} + C_5f_o \qquad (5B\text{-}13)$$

where μ is in micropoise, T in degrees Celsius and

$C_1 = 160.62$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

or for T in degrees Rankine

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147$

Sample Flow Rate

The sample flow rate, at standard conditions, can be found by using the following equation:

$$Q_{s_{ST}} = \frac{V_{ms}}{\theta} \tag{9B-5}$$

However, to calculate the particle cut diameter of the inertial classifier, it is necessary to know the flow rate through the sampler at the actual sampler conditions. This can be accomplished by using the following equation:

$$Q_s = Q_{s_{ST}} \left[\frac{1}{1 - B_{ws}} \right] \left[\frac{T_s}{T_{ST}} \right] \left[\frac{P_{ST}}{P_s} \right]$$

$$= 0.056\, Q_{s_{ST}} \left[\frac{1}{1 - B_{ws}} \right] \left[\frac{T_s}{P_s} \right] \tag{9B-6}$$

Sampler Inlet Reynolds Number

The Reynolds number at the inlet to SRI/EPA Cyclone IV is needed to determine which equation should be used to calculate D_{50}. The inlet Reynolds number may be calculated from the following equation:

$$Re = (8.640 \times 10^3) \frac{P_s M_w}{T_s} \cdot \frac{Q_s}{\mu} \tag{9B-7}$$

Sampler D_{50}

The D_{50} or cut-point of each stage of the chosen particle-sizing device should be calculated for accurate determination of the particle size distribution. The cut-point is primarily a function of the actual flow rate through the sampler and the viscosity and density of the stack gas.

The currently available data concerning calibration of SRI/EPA Cyclone I shows the behavior to be described by the equation

$$D_{50} = 0.15625 \left[\frac{M_w P_s}{T_s} \right]^{-0.2091} \left[\frac{\mu}{Q_s} \right]^{0.7091} \tag{9B-8}$$

For Cyclone IV, the equation for D_{50} takes the form

$$D_{50} = (2.4302 \times 10^{-3}) \left[\frac{\mu}{Q_s} \right]^{1.1701} \left[\frac{1}{C} \right]^{0.5} \left[\frac{P_s M_w}{T_s} \right]^{-0.8700} \tag{9B-9}$$

for a Reynolds number less than 3162 and

$$D_{50} = (1.9723 \times 10^{-2}) \left[\frac{\mu}{Q_s} \right]^{0.8058} \left[\frac{1}{C} \right]^{0.5} \left[\frac{P_s M_w}{T_s} \right]^{-0.3058} \tag{9B-10}$$

for a Reynolds number greater than 3162, where C is the Cunningham slip correction factor and all other terms are as defined above for equation 9B-8.

Unfortunately, the Cunningham slip correction factor, C, is a function of D_{50} as defined by the following equation:

$$C = 1 + (5.7193 \times 10^{-3})\left[\frac{\mu}{D_{50}P_s}\right]\left[\frac{T_s}{M_w}\right]^{1/2} \qquad (9B\text{-}11)$$

Therefore, an iterative solution of equations 9B-9 (or 9B-10) and 9B-11 becomes necessary. First, an initial guess at C (C') should be made by using equation 9B-11, actual stack conditions, and the target D_{50} from the setup calculations. Next, a D_{50}, (D'_{50}) should be calculated from equation 9B-9 (or 9B-10) by using C'. A new value for C (C") should then be calculated by using D'_{50}, and this, in turn, is used to determine a new D_{50} ($D"_{50}$). The iteration should continue in this manner until D'_{50} and $D"_{50}$ agree to within 1%.

If another inertial sizing device is used in conjunction with CSR, the D_{50}'s for each of the stages should be calculated as described in the vendor-supplied operator's manual.

Stack Gas Velocity

The stack gas velocity can be found by using the following equation:

$$v = K_p C_p (\sqrt{\Delta P})\left[\frac{T_s}{P_s M_w}\right]^{1/2} \qquad (9B\text{-}12)$$

Nozzle Velocity

The nozzle velocity, constant for a specific nozzle diameter, may be calculated from the following equation:

$$u = \frac{3.056\ Q_s}{d^2} \qquad (9B\text{-}13)$$

Nozzle ΔP Limits

For each nozzle and stack gas temperature range, limits on acceptable velocity pressure differentials, ΔP_{min} and ΔP_{max}, were calculated from equations 5B-17 and 5B-18 of the setup calculations. These limits should be tabulated and checked against the average velocity pressure differential at each traverse point to determine acceptability of the run as described later in this section.

Percent Isokinetic Sampling

The following equation should be used to determine the percentage of isokinetic sampling:

$$I = \frac{1.677\ T_s \left[0.00267 \cdot V_{lc} + \frac{V_{m\gamma}}{T_m} \left[P_a + \frac{\Delta H}{13.6} \right] \right]}{\theta v P_s A_n} \qquad (9B\text{-}14)$$

Concentration

The concentration of the particulate matter caught by each stage can be calculated by the equation below:

$$C'_n = 0.0154 \left[\frac{M_n}{V_{MS}} \right] \qquad (9B\text{-}15)$$

DATA ANALYSIS FOR EGR

Dry Gas Meter Volume

The sample volume measured by the dry gas meter can be corrected to standard conditions (68°F and 29.92 in. Hg) by using the following equation:

$$V_{MS} = (V_{m\gamma}) \left[\frac{T_{ST}}{T_m} \right] \left[\frac{P_a + \frac{\Delta H}{13.6}}{P_{ST}} \right]$$

$$= 17.65\ (V_{m\gamma}) \left[\frac{P_a + \frac{\Delta H}{13.6}}{T_m} \right] \qquad (9B\text{-}16)$$

Water Vapor Volume

The volume of the water vapor collected from flue gas is calculated as follows:

$$V_{WS} = V_{lc} \left[\frac{\rho_{H_2O}}{M_{H_2O}} \right] \left[\frac{R_u T_{ST}}{P_{ST}} \right] = 0.04707\ (V_{lc}) \qquad (9B\text{-}17)$$

Percent Moisture Content

The moisture content of the stack (or sample) gas is calculated by the equation:

$$B_{ws} = \frac{V_{WS}}{V_{MS} + V_{WS}} \qquad (9B\text{-}18)$$

Water Fraction in Mixed Gas

The moisture content of the mixed gas in the sample device is calculated by the equation:

$$B_{mix} = \left[\frac{Q_s}{Q_t}\right] B_{ws} \qquad (9B\text{-}19)$$

Stack Gas Molecular Weight

The stack gas dry and wet molecular weight is calculated from the following equations:

$$M_d = 32f_o + 44f_c + 28(1 - f_o - f_c) \qquad (5B\text{-}1)$$

$$M_w = M_d(1 - B_{ws}) + 18B_{ws} \qquad (5B\text{-}2)$$

The wet molecular weight of the mixed gas is calculated from the following equation:

$$M_{wm} = M_d(1 - B_{mix}) + 18B_{mix} \qquad (9B\text{-}20)$$

Mixed Gas Viscosity

The viscosity of the mixed gas, μ_m, may be calculated from the following equation (Williamson et al., 1983):

$$\mu_m = C_1 + C_2T_s + C_3T_s^2 + C_4B_{mix} + C_5f_O \qquad (9B\text{-}21)$$

where μ_m is in micropoise, T in degrees Celsius and

$C_1 = 160.6Z$
$C_2 = 0.42952$
$C_3 = 1.0483 \times 10^{-4}$
$C_4 = -74.143$
$C_5 = 53.147$

or for T in degrees Rankine

$C_1 = 51.05$
$C_2 = 0.207$
$C_3 = 3.24 \times 10^{-5}$
$C_4 = -74.143$
$C_5 = 53.147$

Sample Flow Rate

The sample flow rate, at standard conditions, can be found by using the following equation:

$$Q_{s_{ST}} = \frac{V_{MS}}{\theta} \qquad (9B\text{-}22)$$

The sample flow rate at the actual sampler conditions may be determined by using the following equation:

$$Q_s = Q_{s_{ST}}\left(\frac{1}{1 - B_{ws}}\right)\left(\frac{T_s}{T_{ST}}\right)\left(\frac{P_{ST}}{P_s}\right)$$

$$= 0.056\, Q_{s_{ST}}\left(\frac{1}{1 - B_{ws}}\right)\left(\frac{T_s}{P_s}\right) \qquad (9B\text{-}23)$$

Total (Cyclone) Flow Rate

The total flow of mixed gas through the sampler is monitored by a laminar flow element (LFE). The flow rate through this device can be determined by using the following equation:

$$Q_{t_{ST}} = \left[S_t \Delta P_t\left(\frac{\mu_{ST}}{\mu_L}\right) + W_t\right]\left(\frac{T_{ST}}{T_L}\right)\left(\frac{P_L}{P_{ST}}\right)$$

$$= 17.65\left[S_t \Delta P_t\left(\frac{180.1}{\mu_L}\right) + W_t\right]\left(\frac{P_L}{T_L}\right) \qquad (9B\text{-}24)$$

However, to calculate the particle cut diameter of the inertial classifier it is necessary to know the flow rate through the sampler at the actual sampler conditions. This can be accomplished by using the following equation:

$$Q_t = Q_{t_{ST}}\left(\frac{1}{1 - B_{mix}}\right)\left(\frac{T_s}{T_{ST}}\right)\left(\frac{P_{ST}}{P_s}\right)$$

$$= 0.056\, Q_{t_{ST}}\left(\frac{1}{1 - B_{mix}}\right)\left(\frac{T_s}{P_s}\right) \qquad (9B\text{-}25)$$

Percent Recycle

The average percent recycle may be calculated by the following equation:

$$PR = \left(\frac{Q_t - Q_s}{Q_t}\right) \times 100 \qquad (9B\text{-}26)$$

Sampler Inlet Reynolds Number

The Reynolds number at the inlet to SRI/EPA Cyclone IV is needed to determine which equation should be used to calculate D_{50}. The inlet Reynolds number may be calculated from the following equation:

$$Re = (8.640 \times 10^3) \frac{P_s M_w}{T_s} \cdot \frac{Q_s}{\mu} \qquad (9B\text{-}27)$$

Sampler D_{50}

The D_{50} or cut-point of each stage of the chosen particle-sizing device should be calculated for accurate determination of the particle size distribution. The cut-point is primarily a function of the actual flow rate through the sampler and the viscosity and density of the stack gas.

The currently available data concerning calibration of SRI/EPA Cyclone I shows the behavior to be described by the equation

$$D_{50} = 0.15625 \left[\frac{M_{wm} P_s}{T_s} \right]^{-0.2091} \left[\frac{\mu_m}{Q_t} \right]^{0.7091} \qquad (9B\text{-}28)$$

For Cyclone IV, the equation for D_{50} takes the form

$$D_{50} = (2.4302 \times 10^{-3}) \left[\frac{\mu_m}{Q_t} \right]^{1.1791} \left[\frac{1}{C} \right]^{0.5} \left[\frac{P_s M_{wm}}{T_s} \right]^{-0.6790} \qquad (9B\text{-}29)$$

for a Reynolds number less than 3162 and

$$D_{50} = (1.9723 \times 10^{-2}) \left[\frac{\mu_m}{Q_t} \right]^{0.8058} \left[\frac{1}{C} \right]^{0.5} \left[\frac{P_s M_{wm}}{T_s} \right]^{-0.3058} \qquad (9B\text{-}30)$$

for a Reynolds number greater than 3162, where C is the Cunningham slip correction factor and all other terms are as defined above for equation 9B-8.

Unfortunately, the Cunningham slip correction factor, C, is a function of D_{50} as defined by the following equation:

$$C = 1 + (5.7193 \times 10^{-3}) \left[\frac{\mu_m}{D_{50} P_s} \right] \left[\frac{T_s}{M_{wm}} \right]^{1/2} \qquad (9B\text{-}31)$$

Therefore, an iterative solution of equations 9B-9 (or 9B-10) and 9B-11 becomes necessary. First, an initial guess at C (C') should be made by using equation 9B-11, actual stack conditions, and the target D_{50} from the setup calculations. Next, a D_{50}, (D'_{50}) should be calculated from equation 9B-9 (or 9B-10) by using C'. A new value for C (C") should then be calculated by using D'_{50}, and this, in turn, is used to determine a new D_{50} ($D"_{50}$). The iteration should continue in this manner until D'_{50} and $D"_{50}$ agree to within 1%.

If another inertial sizing device is used in conjunction with CSR, the D_{50}'s for each of the stages should be calculated as described in the vendor-supplied operator's manual.

Stack Gas Velocity

The stack gas velocity can be found by using the following equation:

$$v = K_p C_p (\sqrt{\Delta P}) \left[\frac{T_s}{P_s M_s} \right]^{1/2} \qquad (9B\text{-}32)$$

Percent Isokinetic Sampling

The following equation should be used to determine the percentage of isokinetic sampling:

$$I = \frac{1.677\ T_s \left[0.00267 \cdot V_{lc} + \frac{V_{m1}}{T_m} \left(P_a + \frac{\Delta H}{13.6} \right) \right]}{\theta v P_s A_n} \qquad (9B\text{-}33)$$

Concentration

The concentration of the particulate matter caught by each stage can be calculated by the equation below:

$$C'_m = 0.0154 \left[\frac{M_p}{V_{MS}} \right] \qquad (9B\text{-}34)$$

ACCEPTANCE CRITERIA

To be acceptable, each run must meet the following criteria:

1) If the percent isokinetic falls within 100±10%, the velocity at one point may be outside the limits for the nozzle; otherwise, the velocity at each traverse point must be within the velocity limits for the nozzle.

2) For single-stage samplers

- D_{50} of Cyclone I must be 10±1μm.
- D_{50} of Cyclone IV must be 2.5±0.25 μm.

For multiple-stage samplers:

- One stage cut must be equal to or greater than 10 μm with two succeeding size cuts below 10 μm.

- One stage cut must be equal to or greater than 2.5 μm with two succeeding size cuts below 2.5 μm.

- Separation between successive size cuts must be no more than a factor of 2 and no less than a factor of 1.5.

- The product of jet velocity and size cut for each stage with a cut above 2 μm should satisfy the criteria given by McCain et al. (1986).

SYMBOLS FOR SECTION 9B

A_n	Cross-sectional area of sampling nozzle, ft^2
B_{mix}	Proportion by volume of water vapor in mixed gas, dimensionless
B_{ws}	Proportion by volume of water vapor in the gas stream, dimensionless
C	Cunningham slip correction factor
C'_s	Concentration of particulate matter, gr/dscf
C_p	Pitot tube coefficient, dimensionless
$\bar{D}$	The velocity-weighted average of D
D_j	Average value of D for each nozzle size
D_{50}	Diameter of particles having a 50% probability of penetration, μm
d	Nozzle inlet diameter, in.
f_c	CO_2 fraction
f_o	O_2 fraction
I	Percent isokinetic sampling
K_p	85.48 ft/s (lb/mole-°R)
M_d	Dry mlecular weight of stack gas, lb/mole
M_p	Mass of collected particulate (either per stage or total), mg
M_w	Net molecular weight of stack gas, lb/mole
M_{wm}	Wet molecular weight of the mixed gas, lb/mole
M_{H_2O}	Molecular weight of water, 18 lb/mole

n	Number of components changes
P_a	Ambient pressure, in. Hg
P_L	Absolute pressure at LFE inlet, in. Hg
P_s	Absolute stack pressure, in. Hg
P_{ST}	Absolute pressure at standard conditions, 29.92 in. Hg
PR	Recycle ratio at stack conditions, percent
Q_s	Flow rate through the sampler (sampler conditions, wet), acfm
$Q_{s_{ST}}$	Sample flow rate (standard conditions), ft^3/min
Q_t	Total (mixed) flow rate through the sampler (sampler conditions), acfm
$Q_{t_{ST}}$	Total flow rate through the sampler (standard conditions, dry basis), dscfm
Re	Reynolds number
Ru	Ideal gas constant, 21.83 in. Hg-ft^3/mole-°R
S_t	Total flow LFE calibration constant
t_j	Run time for each nozzle size, min
T_L	LFE temperature, °R
T_m	Average gas meter temperature, °R
T_s	Absolute stack temperature, °R
T_{ST}	Absolute temperature at standard conditions, 528 °R
u	Nozzle velocity, ft/s
v	Stack gas velocity, ft/s
V_{lc}	Total volume of liquid collected in impingers or condenser/silica gel, ml
V_m	Volume of gas sample flow through the dry gas meter (meter conditions), ft^3
V_{MS}	Volume of gas sample flow through the dry gas meter (standard conditions), ft^3

V_{ws}	Volume of water vapor in the gas sample (standard conditions), ft^3
W_t	Total flow LFE calibration constant
ΔP	Velocity pressure head, in. H_2O
ΔP	Pressure drop across the total flow LFE, in. H_2O
ΔH	Average pressure drop across the orifice, in. H_2O
ρ_{H_2O}	Density of water, 1 g/ml
θ	Total run time, min
μ	Stack gas viscosity, μp
μ_L	Viscosity of the gas at LFE conditions, μp
μ_m	Viscosity of the mixed gas, μp
μ_{ST}	Viscosity of standard gas (180.1 μp)
γ	Gas meter calibration constant
13.6	Specific gravity of mercury

SECTION 10

MAINTENANCE

Maintenance procedures for a CSR system used for sampling either $PM_{2.5}$ alone or $PM_{2.5}$ with PM_{10} are the same as those outlined for PM_{10} in the CSR or EGR operators manual.

SECTION 11

AUDITING PROCEDURES

The same auditing procedures are recommended when using CSR or EGR for $PM_{2.5}$ determinations in conjunction with or in place of PM_{10} determinations. These procedures are described in the operators manual (CSR or EGR) and will not be repeated here.

SECTION 12

RECOMMENDED STANDARDS FOR ESTABLISHING TRACEABILITY

All appropriate elements of the CSR or EGR system used for $PM_{2.5}$ determinations should be traceable to a standard of reference, as prescribed in the respective operators manual.

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